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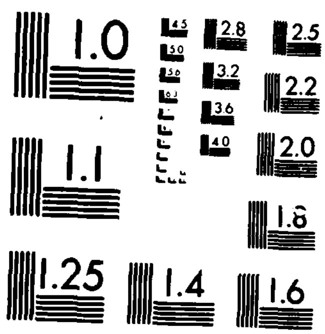

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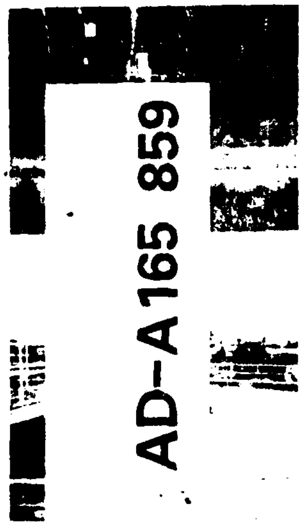

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A REVIEW AND EVALUATION OF RELIABILITY CONCEPTS FOR DESIGN OF WATER DISTRIBUTION SYSTEMS

by

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This study assembles information related to the applicability of mechanical reliability concepts to the evaluation of water distribution systems. Included in the report is a detailed review of water resources and reliability literature and development of a conceptual basis for a technique or methodology to apply reliability concepts to the design and evaluation of water distribution systems.

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20. ABSTRACT (Continued).

A comprehensive review of the reliability literature indicates that even the term "reliability" is ill defined when applied to the analysis of water distribution systems. The concept of availability proved to be a more valuable concept. Methods for quantifying availability of discrete water distribution system components are developed. Specific examples of pump station and pipe reliability analysis are presented.

An extensive list of applicable references is included as Appendix A. Of primary interest to the designer of water distribution systems is the inventory of computer codes available for reliability analysis.

PREFACE

This report was prepared as part of the Water Supply and Conservation Research and Development Program conducted by the US Army Corps of Engineers. Specifically, preparation of this report was funded under the Water Supply System Design work unit (31733).

The work was performed during the period from October 1983 to December 1984 by the Department of Civil Engineering, University of Texas at Austin (UT), and the Water Supply and Waste Treatment Group (WSWTG), Environmental Engineering Division (EED), Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES). The work was conducted at WES under the direct supervision of Mr. Norman R. Francingues, Chief, WSWTG; and under the general supervision of Mr. Andrew J. Green, Chief, EED; and Dr. John Harrison, Chief, EL.

Authors of this report were Dr. Larry W. Mays, UT, and Mr. M. John Cullinane, WES. The report was edited by Ms. Jamie W. Leach, WES Publications and Graphic Arts Division.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
gallons per minute	3.785412	cubic decimetres per minute
horsepower (550 foot-pounds per second)	745.6999	watts
inches	25.4	millimetres
miles (US statute)	1.609347	kilometres

A REVIEW AND EVALUATION OF RELIABILITY CONCEPTS FOR DESIGN OF WATER DISTRIBUTION SYSTEMS

PART I: INTRODUCTION

Background

1. The American Water Works Association (AWWA) (1974) defines a water distribution system as "including all water utility components for the distribution of finished or potable water by means of gravity storage feed or pumps through distribution-pumping networks to customers or other users, including distribution-equalizing storage." The design or extension of a water distribution system generally involves large capital outlays as well as the continuing operation, maintenance, and repair costs. Because of the complexity of the problems arising from the large number of design components and their interaction, automated procedures that result in reliable, but minimum cost, designs are desired. Conventional design approaches consist of selecting a network configuration, pipe sizes, reservoir sizes and elevations, and pumping facilities using a trial and error procedure that attempts to find a workable design representing a low-cost solution. No guarantee can be made that the resulting distribution system is a minimum cost solution nor is any measure made of the reliability of the designed system.

2. Considerable emphasis has recently been placed on the problem of the state of decay in the Nation's infrastructure because of its importance to the needs of society and industrial growth. Large capital expenditures will be needed to bring the concerned systems to higher levels of serviceability and to create a vigor in the US industrial competitiveness in the world. One of the most vital services is an adequate water supply system, without which industry cannot survive.

3. The lack of adequate water supply systems is due to the deterioration of aging water supply systems in older urbanized areas and/or to the inadequate capacity of water supply systems in many areas that are undergoing rapid urbanization, such as in the southwestern United States. In other words, methods for the evaluation of the Nation's water supply services need to consider not only the rehabilitation of existing urban water supply

systems, but also the future development of new water supply systems to serve expanding population centers. Both the adaptation of existing technologies and the development of new, innovative technologies will be required to improve the efficiency and cost-effectiveness of future and existing water supply systems and facilities necessary for industrial growth.

4. Traditionally, investments in infrastructure maintenance have been small and given minor attention. However, a US Environmental Protection Agency (EPA) survey (Clark, Stafford, and Goodrich 1982) of previous water supply projects concluded that the distribution facilities in water supply systems account for the largest cost item in future maintenance budgets. The aging, deteriorating distribution systems in many areas raise tremendous maintenance decisionmaking problems which are further complicated by the expansion of existing systems. Deterioration of the water distribution systems in many areas has translated into a high proportion of unaccounted-for water due to leaks, which not only is a loss of a valuable resource, but also raises concerns about unsafe drinking water caused by possible contamination through cracked pipes. As an example, the following percentages of water lost through leaks have been reported in the literature: 17 percent in Boston, 15 percent in St. Louis, 15 percent in Cleveland, 14 percent in Pittsburgh, and 14 percent in Tulsa (Choate and Walter 1981). Many have estimated the capital needs to rehabilitate urban water distribution systems in the United States on the order of $75 to $110 billion (1972 dollars) ranging over the next 20 years (Choate and Walter 1981).

5. The deferral of critical maintenance causes the reliability of existing systems to decrease. Recently some municipalities have been more willing or able to finance rehabilitation of deteriorating pipelines. Other municipalities, however, still defer needed maintenance and replacement of system components until some catastrophic event occurs. Water main failures have been extensive in many cities. As an example, in 1973 in Houston, Tex., there were 5,149 breaks in the 3,998 miles of water mains, which is 1,290 breaks per year per 1,000 miles of mains.* In New Orleans, there was an average of 680 breaks per year per 1,000 miles of mains in the 1,519 miles of mains during the period 1969-1978.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

6. Water utilities are implemented to construct, operate, and maintain water supply systems. The basic function of these water utilities is to obtain water from a source, treat the water to an acceptable quality, and deliver the desired quantity of water at the desired time. The analysis of a water supply system is often devoted to the evaluation of one or more of the five major system components: source, raw water transmission, treatment system, storage system, or distribution system. The storage system consists of both raw water storage and finished water storage.

7. To ensure reliable delivery of finished water to the user, the water distribution system must be designed to accommodate a range of expected loading conditions. For example, water system components may be designed to meet maximum day, maximum hourly, average day, average hourly, or maximum instantaneous demands. Fire flow demand may also be superimposed on these "normal" demand events. In addition, the system must be designed to accommodate abnormal conditions such as broken pipes and appurtenances; mechanical failure of systems such as pumps, valves, control systems; power outages; failure of storage facilities; system contamination; and inaccurate demand projections. Each of these conditions must be examined with an emphasis on describing its impact on the system, developing relevant measures of system performance, and designing into the system the capacity required to handle emergency conditions with an acceptable measure of reliability.

8. A review of the literature (Part II) reveals that there is currently no universally accepted definition or measure of the reliability of water distribution systems. Reliability is usually defined as the probability that a system performs its mission within specified limits for a given period of time in a specified environment. For a large system, with many interactive subsystems (such as a water distribution system), it is extremely difficult to analytically compute the mathematical reliability. Accurate calculation of a mathematical reliability requires knowledge of the precise reliability of the basic subsystems or components and the impact on mission accomplishment caused by the set of all possible subsystem (component) failures.

9. The so-called "optimal" or "minimum" cost design of water distribution systems has been approached from many different directions, including the use of several types of optimization techniques. These techniques are reviewed in Part II. None of these approaches are completely satisfactory because of their many limitations. Most of the approaches place emphasis on

designing the water distribution system to function under normal loading conditions using peak hourly demands, etc. Very little work has been done on abnormal or emergency loading conditions such as fire demands, pump failure, control valve failure, power outages, and broken links.

10. Many researchers, municipal engineers, urban planners, institutes, government agencies, etc., have discussed the need to develop explicit measures and methodologies to evaluate water distribution system reliability and performance under emergency loading conditions. At present, there is no accepted definition or measure of the reliability of water distribution systems. Some researchers have proposed candidate approaches using concepts of reliability factors, economic loss functions, forced redundancy in the designs, etc. All of these approaches have limitations in problem formulation and/or solution technique. Some investigators discuss the need to explicitly incorporate measures of reliability into optimization models to predict system operation under emergency loading conditions. At present, however, no "optimization-reliability" evaluation or design technique with general application has been developed.

11. While the Corps of Engineers, in its Civil Works mission, does not have general authority to construct or operate water distribution systems, the field operating agencies are often called upon to solve water distribution problems as part of Section 22 studies or specifically authorized studies. In addition, the Corps is directly responsible for planning, design, and construction of water distribution systems to serve military installations and Civil Works recreation areas. These Corps activities in the implementation of water distribution systems require the evaluation of alternative system plans and designs. The application of reliability engineering concepts to the evaluation of water distribution system component reliability can help to ensure that reasonable trade-offs between cost and reliability will be achieved.

Purpose and Scope

12. The major purpose of this study was to assemble information related to the applicability of reliability concepts to the evaluation of water distribution systems. This included a detailed review of water resources and reliability literature and development of a conceptual basis for a technique

or methodology to apply reliability concepts to the design and evaluation of water distribution systems.

13. The following work elements have been performed in order to accomplish the purpose described above:

- a. A detailed review of the water resources literature was made to determine and evaluate the work related to steady-state simulation models, optimization approaches, reliability evaluation, and pipe and pump failure and replacement analysis.
- b. A detailed review was performed of the reliability literature including: electronics literature, power systems literature, chemical engineering literature, mechanical engineering literature, operations research literature, and various other proceedings and textbooks.
- c. The availability of commercial computer codes was evaluated for the reliability analysis of networks.

Organization of Report

14. This report is organized into separate parts describing the results of the state-of-the-art review of water distribution system reliability analysis:

- a. A review of previous work in water distribution system analysis and reliability evaluation is presented in Part II.
- b. Methods for evaluating the reliability of individual water distribution system components are presented in Part III.
- c. Techniques for evaluating the reliability of systems are presented in Part IV.
- d. Examples for evaluation of pumping station and pipe reliability and availability are presented in Part V.
- e. Conclusions and recommendations are presented in Part VI.
- f. Additional references on reliability analysis are presented in Appendix A, while Appendix B lists the available computer codes for reliability analysis.

PART II: PREVIOUS WORK IN WATER DISTRIBUTION SYSTEM ANALYSIS

15. This section presents a summary of previous work on the analysis of water distribution networks. Sections are included for four major classifications of analytical techniques. First, models that have been developed for the steady-state analysis of flow in water distribution networks are discussed. Second, models that have been developed for the optimal (usually minimum cost) design of water distribution systems are presented. Third, a general description of the very few efforts in the literature dealing with the reliability of water distribution systems is presented. Finally, studies incorporating both reliability and maintenance considerations are discussed.

Network Analysis Approaches

16. Numerous models for the steady-state analysis of flow in water distribution networks have been reported in the literature. A brief description of the physical laws is given first, then a brief outline of the various types of network solvers is presented. The equation of continuity for each node can be expressed as

$$\sum_{i=1}^{N} Q_{ji} + b_j = 0 \qquad j = 1 \ldots N \tag{1}$$

where

N = total number of nodes in the network

Q_{ji} = flow from node j to node i

b_j = external flow (consumption) from node j

The loop equations describe the continuity of head around closed paths in a network as

$$\sum_{k \in K_\ell} \Delta H_k = 0 \qquad \ell = 1 \ldots L \tag{2}$$

where

k = k-th link

K_ℓ = the set of links in the ℓ-th loop

ΔH_k = head loss for the k-th link

L = the total number of loops in the network

The path equations describe the continuity of head or energy along any continuous path through a network as

$$H_{e_p} = H_{b_p} - \sum_{k \epsilon K_p} \Delta H_k \qquad p = 1 \ldots P \tag{3}$$

where

H_{e_p} = head at the end of the path

H_{b_p} = head at the beginning of the path

K_p = the set of links for the p-th path

17. Network solvers are computer programs designed to solve the steady-state flow problem using the node equation, the loop equations, the path equations, or a combination of these. Mechler (1970), Shamir (1973), Jeppson (1976), and Stephenson (1976 and 1984) have given surveys of network solvers. The more popular network solvers include the Hardy Cross method, Newton-Raphson method, and graph theory methods. Table 1 lists various selected water distribution network solvers.

Optimization Approaches

18. The optimal design of water distribution systems has been approached using a number of optimization tools. These models have been developed for determining pipe diameters, network layout, pump capacities, heights of elevated reservoirs, valve location, and other design parameters. The objective functions are to minimize costs including acquisition, operation, and maintenance costs. The capabilities of the various models include the type of system analyzed (branched and/or looped), the number of sources allowed (single or multiple), and the number of loading (demand) design

conditions handled. The solution techniques range from linear programming to nonlinear programming.

19. A general statement of the optimization problem (minimizing cost) for designing looped distribution systems subject to satisfying steady-state conditions and minimum head levels under single loading conditions can be stated as:

$$\mathrm{Min}\left[\sum_{k=1}^{NLINK} P(L_k,D_k) + \sum_{m=1}^{NPUMP} PU(XP_m,QP_m) + \sum_{n=1}^{NSTOR} PS(XS_n,XV_n)\right] \tag{4}$$

subject to

$$\sum_k Q_{ki} - \sum_k Q_{ik} = b_i \qquad i \in \mathrm{NODES} \tag{5}$$

$$\Delta H_k D_k^{\beta} = K_k Q_k |Q_k|^{n-1} L_k \qquad k = 1 \ldots \mathrm{NLINK} \tag{6}$$

$$H_i = EL_i + \sum_{n,m} (XP_k + XS_m) \qquad i \in \mathrm{NODES} \tag{7}$$

$$HMIN_i \leq H_i \leq HMAX_i \qquad i \in \mathrm{NODES} \tag{8}$$

$$Q_k,\ XP_k,\ XS_k,\ D_k \geq 0 \tag{9}$$

in which

NLINK = the number of potential links in the network

$P[L_k, D_k]$ = cost function for pipes (link) as a function of the length of link k L_k and the diameter D_k

NPUMP = the number of pumps in the network

$PU[XP_m, QP_m]$ = cost function for pumps as a function of the head lift XP_m for pump m and the flow capacity QP_m

NSTOR = the number of elevated storage reservoirs in the system

$PS[XS_n, XV_n]$ = cost function for storage as a function of the storage height XS_n and the storage volume XV_n

Q_k = the flow rate in link k

ΔH_k = the total head loss over link k

K_k = constant which is a function of the links and the unit of measurement of the empirical head loss equation

b_i = external flow (demand) at node i

EL_i = elevation of node i

$HMIN_i$ = the minimum head level at node i

$HMAX_i$ = the maximum head level at node i

20. The objective function (Equation 4) is composed of cost functions for link cost, pump and energy cost, and storage costs which can be expressed in terms of uniform annual costs. The linear system of Equation 5 ensures that conservation of flows is satisfied at each node. Equation 6 determines the head loss and flow direction in each link. Equation 7 states that the total head at each source node is the sum of the nodal heads plus the head added by pumps and storage reservoirs located at the node. Equation 8 expresses the maximum and minimum head bounds. The nonnegativity constraints for the flow rate, pump head lift, storage elevation, and diameter are given as Equation 9.

21. The water distribution problem (expressed as Equations 4-9) is an optimization problem with a nonlinear objective function and nonlinear constraints. The problem is even more difficult if constraints are added to describe how the system operates under emergency loading conditions such as fire demand and broken mains. A considerable amount of research has addressed the water distribution system optimization problem. Walski (1985a) identifies over 60 optimization programs with more being published almost daily. All of these efforts have attempted to solve the problem through simplification in order to apply various types of optimization approaches. At present there is no method for optimal (minimum cost) design of looped distribution systems that is completely satisfactory. An added difficulty in the optimal design of a looped system is that the requirement for redundancy is extremely vague. Existing solution methods also make no real attempt to explicitly generate and evaluate network layouts in terms of their ultimate impact on total systems cost and on reliability of water service.

22. Numerous models have been developed and reported in the literature. Several of these models have only considered branching type networks, including: linear programming approaches by Karmeli, Gadish, and Myers (1968); and dynamic programming by Lai (1970) and Swamee, Kumar, and Khanna (1973).

23. Several models considering looped systems have also been developed.

One of the first models was developed by Shamir (1973) in which the decision variable was pipe diameter. The objective function considered a single loading and was related to energy loss in flow through all the pipes. The steady-state hydraulic solution was obtained by the Newton-Rhapson method with the Jacobian of the solution used to compute the components of the gradient.

24. Several later models for looped systems are listed and compared in Table 2. This table is not complete, but does list the more important models that have been developed. It is obvious that the water distribution optimization problem has not been completely solved and a great deal of work could be performed. The past models have not considered multiple loading for various emergency conditions. These models have made simplifications in cost equations and various constraints to limit the size of the optimization model. There are rather severe limitations to the size of problems that can be solved with these existing models. In addition, these models do not attempt to incorporate any reliability considerations nor do they explicitly consider various network layouts.

Approaches Incorporating Reliability Analysis

25. The previous section briefly described the existing models that have been developed for the minimum cost design of water distribution systems. The emphasis of these models has been on designing the systems to operate under normal loading conditions. Very little effort has been reported in the literature on models that consider emergency loading conditions caused by such events as fire demand, pump failure, or broken pipes.

26. One of the first efforts at considering emergency loading conditions was by de Neufville, Schaake, and Stafford (1971), which examined four primary measures of water distribution system design: (a) overall performance; (b) fail-safe reliability; (c) distribution of performance; and (d) cost. The most significant part of this effort was to quantitatively evaluate water distribution system performance (node load values) under realistic emergency loading conditions and to consider the cost/benefit tradeoffs of the emergency loading conditions. This effort, however, did not explicitly consider any type of reliability evaluation.

27. Damelin, Shamir, and Arad (1972) were the first to explicitly consider reliability measures in the design of water distribution systems. One

of the major premises of this work was that reliability has an economic value. The simulation (reliability) model developed by these investigators was used for evaluating the reliability of supplying a known demand pattern in a given water supply in which shortfalls could be caused by random failures of the pumping equipment. The economic model developed enabled use of the reliability model to compute the cost of the marginal water obtained by improving the reliability of the system.

28. The first objective of Damelin, Shamir, and Arad (1972) was to devise a means of evaluating the reliability of a given set of pumping equipment serving a given demand considering the random nature of pumping equipment failure and repair duration. This tool is then used to examine the effect on reliability of variations in the design and maintenance procedures for various demand patterns. The reliability relationships for various designs, maintenance procedures, and demand patterns are used as a model to evaluate: (a) least cost points on isoreliability surfaces which represent the selection of the pumping to achieve a required level of reliability at a minimum cost; (b) computation of marginal water cost associated with variations in design or maintenance procedures to improve system reliability for a given demand pattern; and (c) computation of marginal water costs for both augmenting a water supply and maintaining the same level of system reliability.

29. The Damelin, Shamir, and Arad (1972) model considered pump interfailure times and repair durations as random variables. The interfailure time was assumed to be exponentially distributed and the repair duration was assumed to be lognormally distributed.

30. Shamir and Howard (1981) used the approach of defining the reliability as the probability that a reliability factor is achieved. The reliability factor for single events or for selected time periods was defined in terms of capacity lost due to failure, measured as a fraction of the demand rate and/or the demand volume. Because the lost capacity is a random variable, then the reliability factor is also a random variable.

31. This study (Shamir and Howard 1981) considered two components (reliability factors) to define the overall reliability: (a) a discharge reliability factor RC defined as

$$RC = 1 - \left(\frac{C}{CT}\right)^n \qquad (10)$$

where

C = discharge lost due to failure

CT = total discharge rate required

n = exponent

and (b) a volume reliability factor RV , defined as

$$RV = 1 - \frac{V}{VT} = 1 - \frac{C \times D}{CT \times D} \tag{11}$$

where

V = shortfall volume

VT = total volume required during the failure event time period

V is simply $C \times D$ where D is the duration of failure and VT is simply $CT \times D$. Shamir and Howard (1981) then expressed the reliability factor as

$$RF = \frac{RC + RV}{2} = 1 - \frac{\left(\frac{C}{CT}\right)^n + \left(\frac{C}{CT}\right)}{2} \tag{12}$$

32. The probability density function pdf of RF was defined as

$$f_{RF}(r) = \left|\frac{dC}{dRF}\right| f_C(c) = \frac{2CT^n}{CT^{n-1} + nC^{n-1}} \quad f_C(c) \tag{13}$$

where $f_C(c)$ = pdf of the lost capacity.

33. Shamir and Howard (1981) discussed the use of both a postulated and an exponential probability density function for the lost capacity. The postulated pdf was expressed as

$$f_C(c) = \frac{m + 1}{CT}\left(1 - \frac{c}{CT}\right)^m \qquad 0 \le c \le CT \tag{14}$$

where $m > 1$ = parameter determined from the data. The exponential distribution is expressed as

$$f_C(c) = \beta e^{-\beta c} \tag{15}$$

34. The model can be extended to determine the length of time it takes before the reliability factor drops below a reference value of the reliability factor RF_o. For annual values the return period is

$$T_{RF_o} = \frac{1}{\lambda P(RF \le RF_o)} = \frac{1}{\lambda F_{RF}(RF_o)} \tag{16}$$

where λ is the reciprocal of the mean time between failures and is the average number of failures per year. The above equation can be used to develop reliability factor-frequency curves which could be used to compare the reliability of alternative systems.

35. The probability that a storage volume S_o can supply the demand during a failure event is

$$P(C \times D \le S_o) = \iint_{\Omega} f_C(d)\ dc\ f_D(d)\ dd \tag{17}$$

assuming that the lost capacity during failure and the repair duration are statistically independent. Considering lost capacities below some specified value C_o, the corresponding reliability factor is RF_o. The reliability is then expressed as a function of the reliability factor (a measure of lost capacity) and the storage as

$$R(RF_o, S_o) = P\left(RF \le RF_o \mid S = S_o\right) = P\left(C \times D < S_o \mid C < C_o\right) \tag{18}$$

36. The reliability can also be expanded to consider standby pumping capacity SBC_o as

$$R(RF_o, S_o, SBC_o) = \iint_{\Phi} f_C(c)\ dc\ f_D(d)\ dd \tag{19}$$

The region of integration Φ is illustrated in Figure 1 and the trade-off between storage and standby pumping capacity to achieve a specified

reliability for fixed reliability factors is illustrated in Figure 2.

37. For each reliability curve it is possible to compute the cost of the combinations of storage and standby pumping capacity to compute the least-cost combinations as shown in Figure 2. Relationships can then be plotted for the minimum cost versus reliability R for fixed reliability factors RF as shown in Figure 3, and/or the minimum cost versus RF for fixed values of R as shown in Figure 4.

Approaches Incorporating Reliability and Maintenance

38. Several articles have been reported in the literature dealing with criteria and methods for analyzing the replacement and/or repair of water distribution pipes. The aging of pipes causes a decrease in their carrying capacity and they become more prone to breakage. The reasons for breaks include: quality and age of the pipe; quality of installation; type of environment, e.g. external corrosion, temperature conditions, frost conditions, soil movement, external loads, etc; and service conditions such as operating pressures and water hammer.

39. The cost of pipe breaks can represent a significant portion of the maintenance costs for a water distribution system. As a result the decision of whether to repair or replace the pipe must be considered from an economic viewpoint. Stacha (1978) outlined several criteria that should be considered in the final decision to replace a water main. These criteria include comparison of annual costs for repair and replacement; adequacy of the capacity of the existing main; effect on water quality by the internal condition of the pipe; hazards of existing main to the safety of persons and property; effect of increasing demands on the existing pipes; frequency of failure; and street conditions.

40. Shamir and Howard (1979) developed a procedure to schedule pipe replacement based upon forecasted number of breaks of existing pipe; forecasted number of breaks in the new pipe; cost of repairing one break; cost of replacing the existing pipe; and the discount rate. Regression equations of the form

$$N(t) = N(t_o)e^{A(t-t_o)} \qquad (20)$$

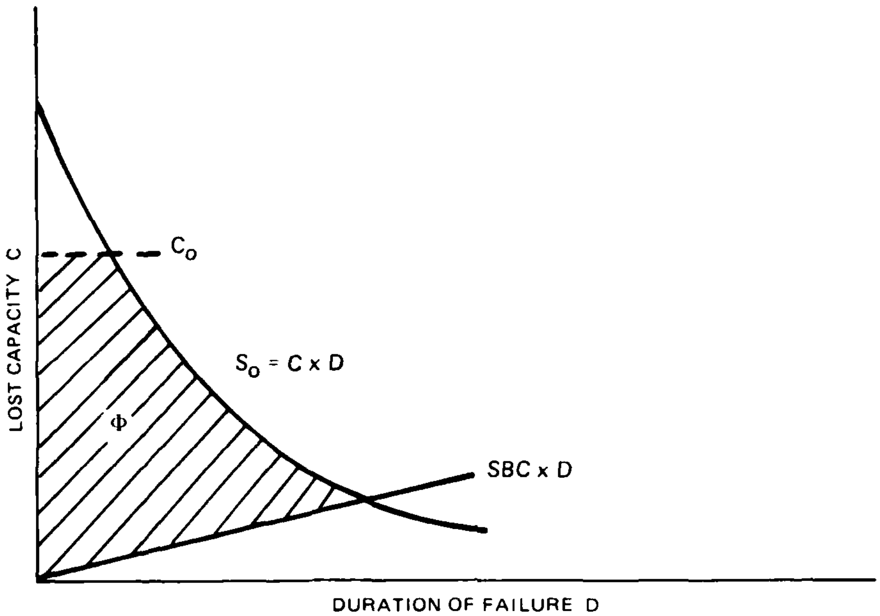

Figure 1. Region of integration

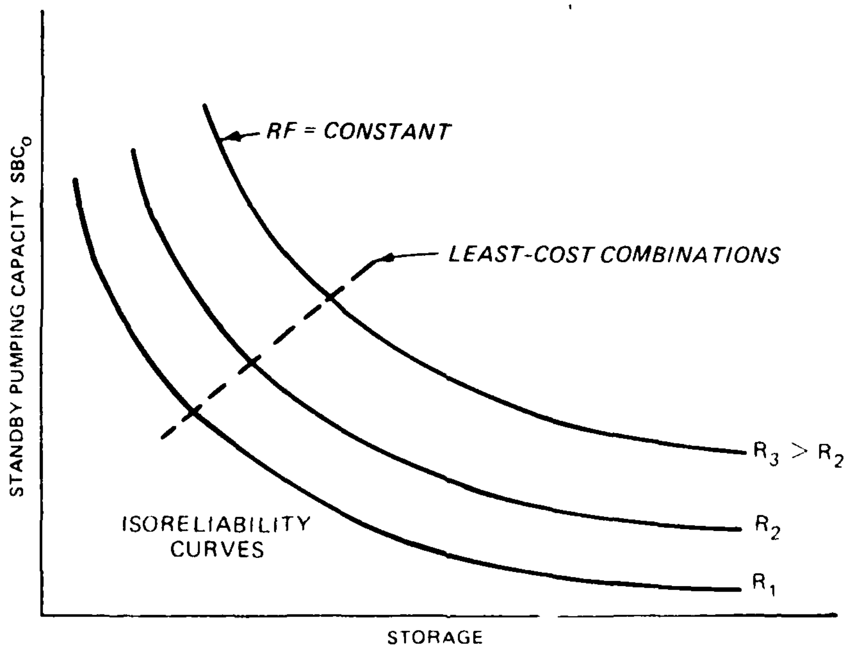

Figure 2. Trade-off between storage and standby pumping capacity to achieve a given reliability for fixed reliability factors

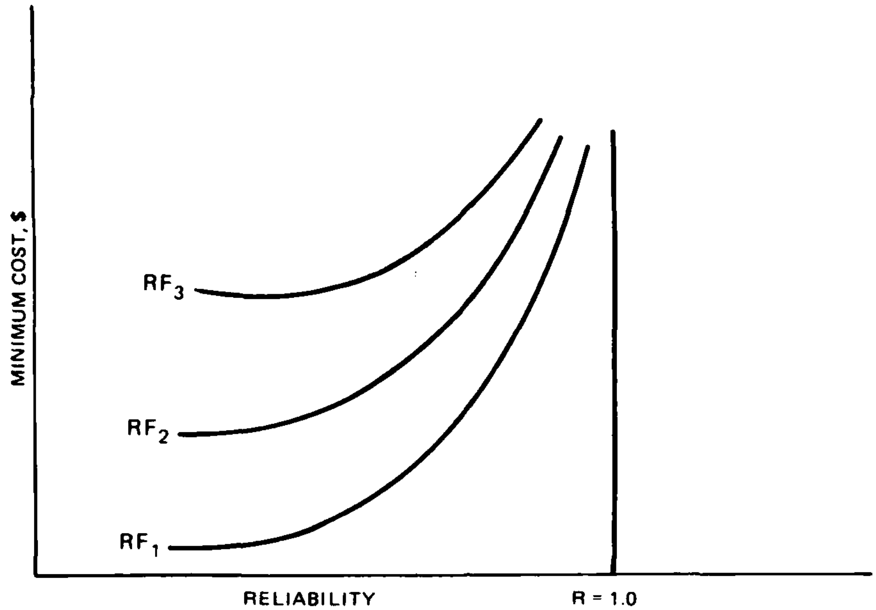

Figure 3. Reliability versus minimum cost

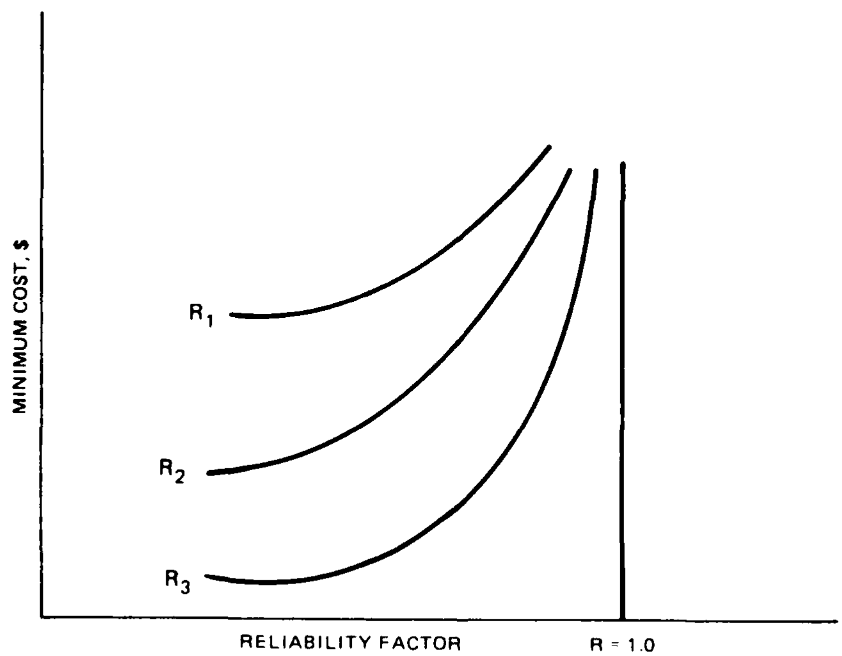

Figure 4. Reliability factor versus minimum cost

where

$N(t)$ = number of breaks per 1,000-ft length of pipe in year t

t = time in years

t_o = base year when pipe was installed

A = growth rate coefficient

41. The cost of repairing the breaks in 1,000 ft of pipe in year t was expressed as

$$C_m(t) = C_b N(t) = C_b N(t_o) e^{A(t-t_o)} \tag{21}$$

where C_b is the cost of repairing a break. The present value of all maintenance cost $P_m(t_r)$ from the year t_p to year t_r for 1,000 ft of pipe is

$$P_m(t_r) = \sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1 + R)^{t-t_p}} = \sum_{t=t_p}^{t_r} \frac{C_b N(t_o) e^{A(t-t_o)}}{(1 + R)^{t-t_p}} \tag{22}$$

where R is the discount rate.

42. The present value in year t_p of replacing 1,000 ft of pipe in year t_r is

$$P_r(t_r) = \frac{C_r}{(1 + R)^{t_r-t_p}} \tag{23}$$

where C_r is the cost of replacement. The optimal timing for replacement is the time t_r that minimizes the total present cost which is stated mathematically as:

$$\min_{t_r} [P_t(t_r)]$$

$$= \min_{t_r} \left[\sum_{t=t_p}^{t_r} \frac{C_b N(t_o)\, e^{A(t-t_o)}}{(1+R)^{t-t_p}} + \frac{C_r}{(1+R)^{t_r-t_p}} \right] \tag{24}$$

Differentiating with respect to t_r and solving for t_r gives

$$t_r = t_o + \frac{1}{A} \ln \left[\frac{\ln\,(1+R)C_r}{N(t_o)C_b} \right] \tag{25}$$

For a linear increase in breaks given by,

$$N(t) = N(t_o) + A(t_p - t_o) \tag{26}$$

the optimal time for replacement is expressed as

$$t_r = t_o + \frac{\ln\,(1+R)C_r}{AN(t_o)C_b} \tag{27}$$

43. Walski and Pelliccia (1982) stated that the exponential Equation 20 fits certain data better than the linear Equation 26. A break prediction model was used of the form,

$$N(t) = C_1 C_2 a e^{b(t-k)} \tag{28}$$

where

$N(t)$ = break rate per year per mile

C_1 = correction factor for previous breaks

C_2 = correction factor for pipe size

a and b = regression coefficients

k = year of pipe installation so that $(t - k)$ is the age of the pipe.

44. Walski and Pelliccia (1982) developed a new criterion to replace

pipes which stated that if a pipes current break rate J is greater than some critical break rate J^*, the pipe should be replaced. The criterion was stated as

$$J > J^* = \frac{5280\ C_r L\ \ln\left(\frac{e^b}{1 + R}\right)}{C_b\left[\left(\frac{e^b}{1 + R}\right)^m - 1\right]} \tag{29}$$

where

J and J^* = breaks per year per mile
C_r = replacement cost
L = fraction of pipe replaced
b = regression coefficient
R = interest rate
C_b = cost of a break
m = period of analysis, years

Walski and Pelliccia (1982) concluded that the Shamir and Howard (1979) approach (Equation 24) is useful for deciding whether to replace entire groups of pipes but Equation 29 is more useful in analyzing the economic replacement on a pipe-by-pipe basis.

45. Walski and Pelliccia (1982) also presented two simplifications to Equation 29. The first is

$$J^* = \frac{5280\ C_r L\ \ln\left(\frac{1 + R}{1 + b}\right)}{C_b} \tag{30}$$

in which b is significant, but the break rate of the future pipe need not be considered such as for most unprotected pipes in fairly corrosive soils. The second is

$$J^* = \frac{5280\ C_r L\ \ln\ (1 + R)}{C_b} \tag{31}$$

in which $b = 0$, i.e. the break rate is not changing significantly with time,

which is the case for most nonmetallic pipes or metallic pipes in noncorrosive soil.

46. Clark, Stafford, and Goodrich (1982) used the analysis by Shamir and Howard (1979) to define the number of maintenance events in a given section of pipe as

$$N(t) = Ke^{GR(t-t_o)} \tag{32}$$

where

$N(t)$ = number of maintenance events

K = a constant

GR = growth rate coefficient

t = number of years from installation

t_o = number of years from installation to the first maintenance event

The optimal time to replacement was the same as the Shamir and Howard (1979) approach. This effort also developed regression equations for the number of years from installation to first repair and for the number of repairs.

47. Walski (1982, 1985b) considered the economic analysis of the rehabilitation of water mains. This analysis considered that the cleaning and relining of water transmission lines is economical if the costs are less than the savings in energy and pumping capacity which occur because of the increased carrying capacity of the pipe. The criteria developed can be used to determine if it is economical to clean and relign a pipe for two cases: flow is not significantly changed by rehabilitation of the pipe, or the system is looped so that the change in carrying capacity significantly changes flow.

48. The decision criterion was to rehabilitate if the cost for rehabilitation is less than the extra cost for pumping energy and additional equipment required to force water through the main with a low Hazen-Williams C-factor, stated as

$$c_r < (c_p - \bar{c}_p) + (c_e - \bar{c}_e)spwf \tag{33}$$

where

c_r = cost of rehabilitation

c_p = cost of pumping equipment required with no rehabilitation

$\bar{c}_p$ = cost of pumping equipment with rehabilitation

c_e = cost of energy loss in pipe without rehabilitation

$\bar{c}_e$ = cost of energy loss in pipe with rehabilitation

spwf = series present worth factor for energy cost

A rehabilitation index R was defined as

$$R = (c_p - \bar{c}_p) + (c_e - \bar{c}_e)\ spwf - c_r \tag{34}$$

The cost of energy loss $c_e - \bar{c}_e$ was derived as

$$c_e - \bar{c}_e = \frac{0.1711\ Q_a^{2.85}}{D^{4.87} E}\ P\left(\frac{1}{C^{1.85}} - \frac{1}{\bar{C}^{1.85}}\right) \tag{35}$$

where

Q_a = average flow, gal/min

D = diameter, in.

E = wire-to-water efficiency

P = price of energy, ¢/kwhr

C = Hazen-Williams coefficient

$\bar{C}$ = Hazen-Williams coefficient after rehabilitation

The cost savings (cost of pumping) by rehabilitating the pipes was expressed as

$$c_p - \bar{c}_p = F\Delta h_p = \frac{10.43\ Q_p^{1.85}}{D^{4.87}}\ F\left(\frac{1}{C^{1.85}} - \frac{1}{\bar{C}^{1.85}}\right) \tag{36}$$

where

F = $(pwf)(dc/dh)_p$ = rate of change in cost per change in head loss

pwf = present worth factor based on the year that additional pump capacity is required

dc/dh = rate of change in cost per change in head loss

Δh_p = increase in head provided by pumps

49. Equations 35 and 36 can be substituted into Equation 34 to express R as

$$R = \frac{10.43\ C^*}{D^{4.87}} \left[Q_p^{1.85} F + \frac{Q_a^{2.85} P(\mathrm{spwf})(0.0164)}{E} \right] - c_r \tag{37}$$

in which

$$C^* = \left(\frac{1}{C^{1.85}} - \frac{1}{\bar{C}^{1.85}} \right) \tag{38}$$

The above models were used to develop graphs of the various parameters versus degree of rehabilitation as shown in Figure 5. The approach can be used to determine if it is economical to rehabilitate pipes based on the savings in energy and pumping capacity. Walski (1982) emphasizes that this approach is appropriate for lines fed directly from pumps but not small distribution lines sized for fire flow and being fed from storage tanks.

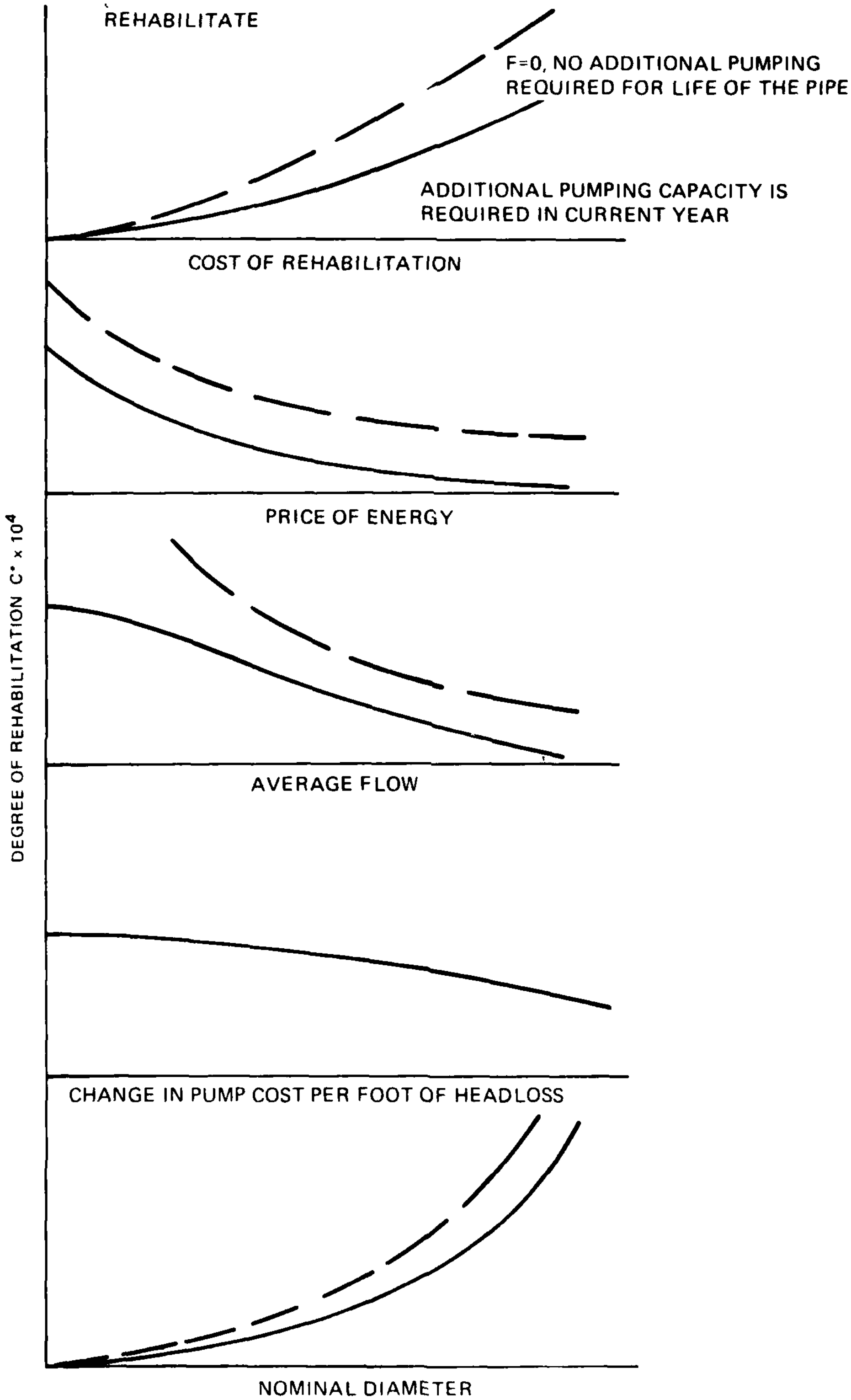

Figure 5. Degree of rehabilitation

PART III: COMPONENT RELIABILITY ANALYSIS

Definitions of Terms

50. The analysis of reliability and availability requires an understanding of some basic terms, which are defined in this section. The concepts represented by these terms will be used in later sections to quantify reliability and availability.

Reliability

51. The reliability $R(t)$ of a component is defined as the probability that the component experiences no failures during the time interval from time zero to time $t(t,o)$, given that it is new or repaired at time zero. Reliability can be defined mathematically as:

$$R(t) = \int_t^\infty f(t)\,dt \tag{39}$$

where $f(t)$ = probability density function of the time to failure. Values for $R(t)$ range between 0 and 1. The probability density function $f(t)$ may be developed from equipment failure data, using various statistical methods; however, in most cases an exponential distribution is assumed.

Unreliability

52. The unreliability $F(t)$ of a component is defined as the probability that the component will fail by time t. Unreliability can be defined mathematically as:

$$F(t) = \int_0^t f(t)\,dt \tag{40}$$

Failure rate

53. The failure rate $r(t)$ is the probability that a component experiences a failure per unit of time t given that the component was operating at time zero and has survived to time t. The quantity $r(t)\,dt$ is the probability that a component fails during time $(t,t+dt)$. Values for $r(t)\,dt$ range from 0 to 1.

Mean time to failure

54. The mean time to failure MTTF is the expected value of the time to failure, stated mathematically as:

$$MTTF = \int_{o}^{\infty} t \times f(t)\, dt \qquad (41)$$

The MTTF is usually expressed in hours.

Probability of repair

55. The probability of repair $G(t)$ is the probability that the component repair is completed before time t, given that the component failed at time zero. Note that the repair process starts with a failure at time zero and ends at the completion of the repair at time t.

Repair rate

56. The repair rate $g(t)$ is the probability that the component is repaired per unit time at time t given that the component failed at time zero and is still not repaired at time t. The quantity $g(t)\, dt$ is the probability that a component is repaired during time $(t,t+dt)$ given that the components failure occurred at time t.

Mean time to repair

57. The mean time to repair MTTR is the expected value of the time to repair a failed component. MTTF is defined mathematically as:

$$MTTR = \int_{o}^{\infty} t \times g(t)\, dt \qquad (42)$$

where $g(t)$ is the probability density function for the repair time. The MTTR is usually expressed in hours.

Mean time between failures

58. The mean time between failures MTBF is the expected value of the time between two consecutive failures. For a repairable component, the MTBF is defined mathematically as:

$$MTBF = MTTF + MTTR \qquad (43)$$

Mean time between repairs

59. The mean time between repairs MTBR is the expected value of the time between two consecutive repairs and equals the MTBF .

Availability

60. The availability $A(t)$ of a component is the probability that the component is in operating condition at time t , given that the component was as good as new at time zero. The reliability generally differs from the availability because reliability requires the continuation of the operational state over the whole interval $(0,t)$. Subcomponents contribute to the availability $A(t)$ but not to the reliability $R(t)$ if the subcomponent that failed before time t is repaired and is then operational at time t . As a result, the availability $A(t)$ is always larger than or equal to the reliability $R(t)$, i.e. $A(t) \geq R(t)$. For a nonrepairable component, it is operational at time t if and only if it has been operational to time t , i.e. $A(t) = R(t)$ for nonrepairable components. As shown in Figure 6, the availability of a nonrepairable component decreases to zero as t becomes larger, whereas the availability of a repairable component converges to a nonzero positive number.

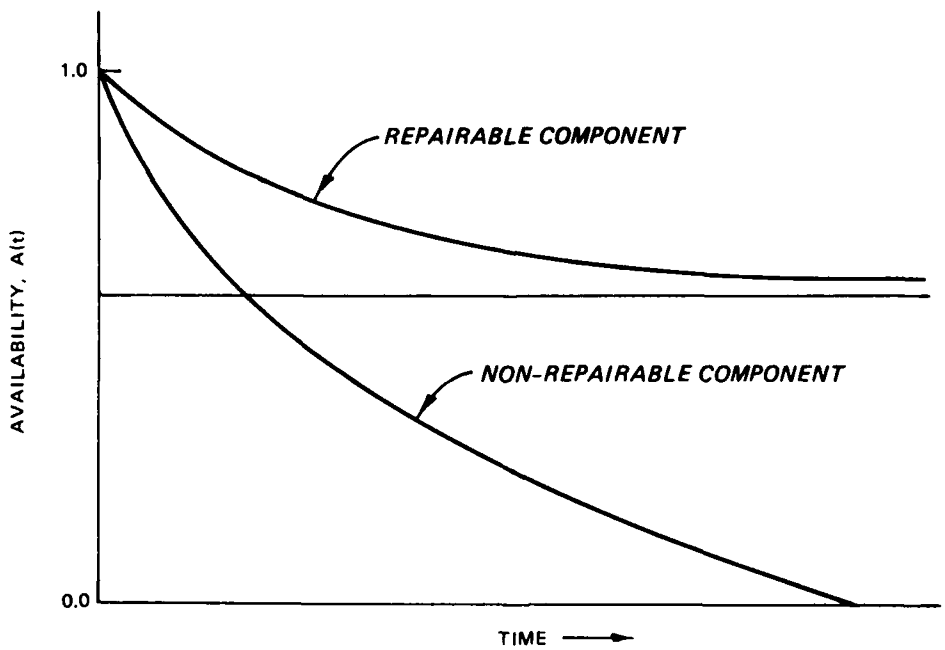

Figure 6. Availability for repairable and nonrepairable components

Unavailability

61. The unavailability $Q(t)$ at time t is the probability that a component is in the failed state at time t, given that it started in the operational state at time zero. The $Q(t)$ is less than or equal to the unreliability $F(t)$ and for nonrepairable components they are equal. Because a component is either in the normal state or failed state at time t, then

$$A(t) + Q(t) = 1 \tag{44}$$

Conditional failure intensity

62. Conditional failure intensity $\lambda(t)$ is the probability that a component fails per unit time at time t, given that it is in the operational state at time zero and is operational at time t. The quantity $\lambda(t)\,dt$ is the probability that a component fails during a small time interval $(t,t+dt)$ given that the component was as good as new at time zero and operational at time t. The quantity $r(t)\,dt$ is the probability that a component fails during the time interval given that the component was repaired at time zero and has been operational to time t. The quantities $\lambda(t)\,dt$ and $r(t)\,dt$ differ because $r(t)\,dt$ assumes the continuation of the operational state to time t or that no failure occurred in the interval $(0,t)$, whereas $\lambda(t)\,dt$ only assumes that the component is operational at time t, i.e. intermediate failures between time zero and time t are not important to the calculation.

$$\lambda(t) = r(t) \qquad \text{general case} \tag{45}$$

$$\lambda(t) = r(t) \qquad \text{nonrepairable component} \tag{46}$$

$$\lambda(t) = r \qquad \text{constant failure rate } r \tag{47}$$

Unconditional failure intensity

63. The unconditional failure intensity $w(t)$ is the probability that a component fails per unit time at time t, given that it started in the operational state at time zero. The unconditional failure intensity is obtained from the analysis of equipment failure data (Henley and Kumamoto 1981).

Expected number of failures

64. The expected number of failures $W(t,t+dt)$, given that the component started into the operational state at time zero, is defined as

$$W(t,t+dt) = \int_{t}^{t+dt} w(t)\,dt \tag{48}$$

For a nonrepairable component, $W(0,t) = F(t)$ and approaches unity as t gets larger. For a repairable component, $W(0,t)$ diverges to infinity as t becomes larger. Typical curves of $W(0,t)$ are shown in Figure 7.

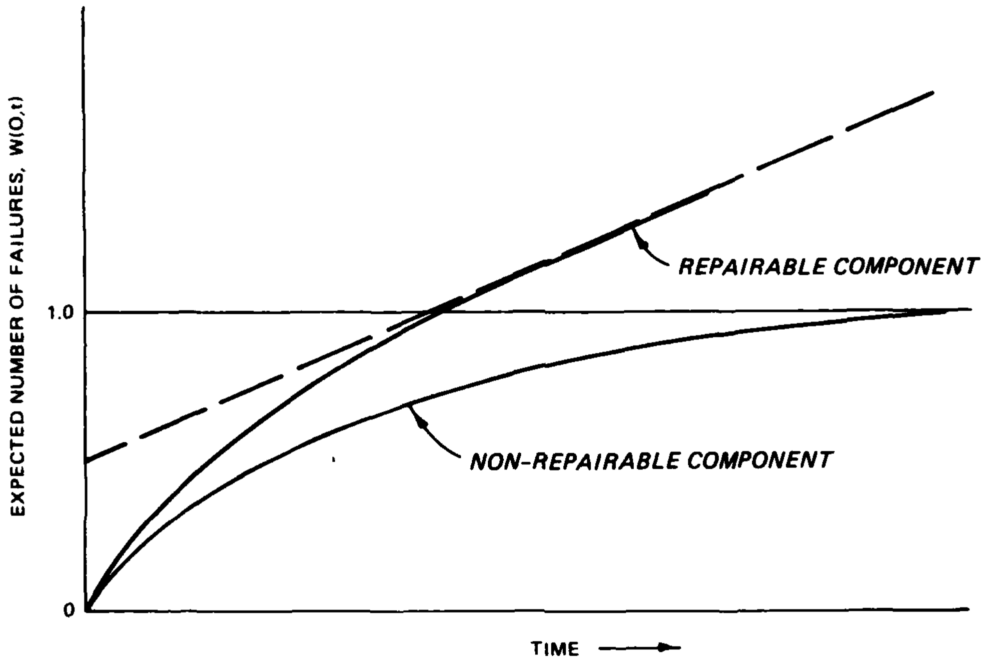

Figure 7. Expected number of failures for repairable and nonrepairable components

Conditional repair intensity

65. The conditional repair intensity $u(t)$ is the probability that a component is repaired per unit time at time t, given that it started into the normal state at time zero and failed at time t. The repair rate $m(t)$ and $u(t)$ differ in a manner similar to the relation between $\lambda(t)$ and $r(t)$.

$$u(t) = m(t) = 0 \quad \text{nonrepairable component} \tag{49}$$

$$u(t) = m \quad \text{constant repair rate } m \tag{50}$$

Unconditional repair intensity

66. An unconditional repair intensity $v(t)$ is the probability that a component is repaired per unit time at time t, given that it started into the operational state at time zero.

Expected number of repairs

67. Expected number of repairs during $(t,t+dt)$ given that the component started into the operational state at time zero is

$$V(t,t+dt) = \int_{t}^{t+dt} v(t)\, dt \tag{51}$$

For a nonrepairable component $V(0,t) = 0$ and for a repairable component, $V(0,t) \to \infty$ as t gets larger.

Density functions

68. The common thread in the analysis of reliability and availability is the selection of an appropriate failure density function. A probability density function or simply a density function is a function that associates with each value of a random variable the probability that this value will be assumed. It is a theoretical model for the frequency distribution of a population of measurements (Mendenhall, Scheaffer, and Wackerly 1981). Density functions are used to model a variety of reliability-associated events including time to failure and time to repair. Some of the more common failure density functions used in reliability analysis and their associated unreliability, failure rate, and mean time to failure functions are presented in Table 3.

69. Because of its relative simplicity for performing reliability analyses, the exponential distribution is probably the most widely used failure density function. The exponential density function is:

$$f(t) = \lambda e^{-\lambda t} \qquad t \geq 0 \, , \, \lambda > 0 \tag{52}$$

where λ is a constant failure rate. The reliability is simply

$$R(t) = e^{-\lambda t} \tag{53}$$

The MTTF is

$$\mathrm{MTTF} = \int_0^{\infty} t \times \lambda e^{-\lambda t}\, dt = \frac{1}{\lambda} \tag{54}$$

The mean time to repair can also be defined using the exponential density function

$$t(t) = ue^{-ut} \tag{55}$$

so that

$$\mathrm{MTTR} = \int_0^{\infty} t \times ue^{-ut}\, dt = \frac{1}{u} \tag{56}$$

The MTTR can be estimated using an arithmetical mean of the time to repair data for various types of components.

Parameter Relationships

70. Henley and Kumamoto (1981) developed a number of relationships between the various reliability (availability) parameters. The more significant of these are summarized in Table 4.

Availability and unavailability for constant failure and repair rates

71. For a constant failure rate and a constant repair rate the analysis of the whole process can be simplified to analytical solutions. Henley and Kumamoto (1981) used Laplace transforms to derive the unavailability as

$$Q(t) = \frac{\lambda}{\lambda + u}\left[1 - e^{-(\lambda+u)t}\right] \tag{57}$$

and the availability

$$A(t) = 1 - Q(t) = \frac{u}{\lambda + u} + \frac{\lambda}{\lambda + u}\, e^{-(\lambda+u)t} \tag{58}$$

The stationary unavailability $Q(\infty)$ and the stationary availability $A(\infty)$ are

$$Q(\infty) = \frac{\lambda}{\lambda + u} = \frac{MTTR}{MTTF + MTTR} \tag{59}$$

$$A(\infty) = \frac{u}{\lambda + u} = \frac{MTTF}{MTTF + MTTR} \tag{60}$$

The following relation is also true

$$\frac{Q(t)}{Q(\infty)} = 1 - e^{-(\lambda+u)t} \tag{61}$$

A summary of the other relations for the whole process for constant failure rates is given in Table 4.

Relations for repair-to-failure
and failure-to-repair processes

72. The probability that a component failure occurs during time interval $(t,t+dt)$, represented by A, given that the component has been normal to time t (represented by C) and the component was repaired at time zero (represented by W) is expressed as

$$P[A|C,W] = \frac{P[A,C|W]}{P[C|W]} \tag{62}$$

where

$P[A,C|W] = f(t)\ dt$

$P[C|W] =$ the reliability $R(t)$

Then $P[A|C,W] = r(t)\ dt$ so that

$$r(t)\ dt = \frac{f(t)\ dt}{R(t)} \tag{63}$$

or
$$r(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)} \tag{64}$$

The reliability is then

$$R(t) = \exp\left[-\int_0^t r(t)\,dt\right] \tag{65}$$

and the unreliability is simply $F(t) = 1 - R(t)$. The density function is

$$f(t) = r(t)\exp\left[-\int_0^t r(t)\,dt\right] \tag{66}$$

73. Similar to the repair-to-failure process, relations can be derived for the failure-to-repair process:

$$m(t) = \frac{g(t)}{1 - G(t)} \tag{67}$$

$$G(t) = 1 - \exp\left[-\int_0^t m(t)\,du\right] \tag{68}$$

$$g(t) = m(t)\exp\left[-\int_0^t m(u)\,du\right] \tag{69}$$

Analysis of the whole process using time to failure data

74. When time to failure data are known, commonly used distributions can be employed in the analysis. For components which have an increasing failure rate with time, the normal, lognormal, or the Weibull distribution with a shape parameter larger than unity could apply.

75. The following analysis will assume that the Weibull distribution applies to the increasing failure rate for water mains. Properties of this distribution are given in Table 3. The unreliability is expressed as

$$F(t) = 1 - \exp\left[-\left(\frac{t-\gamma}{\theta}\right)^{\beta}\right] \tag{70}$$

where

γ = time when the component begins to fail

θ = characteristic life

β = shape parameter of the Weibull slopes

For practical reasons, it is convenient to assume that $\gamma = 0$ so that the above is reduced to

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \tag{71}$$

which reduces to

$$\log\left\{\log\left[\frac{1}{1 - F(t)}\right]\right\} = \beta \log t - \beta \log \theta \tag{72}$$

so that $\left\{\log 1/[1 - F(t)]\right\}$ plots as a straight line against $\log t$ with slope β and y-intercept of $-\beta \log \theta$. To use the Weibull distribution, it is necessary to estimate the two parameters θ and β using time to failure data. The data are plotted on Weibull paper and a straight line is fitted to the data.

76. The mean time to failure is

$$\mathrm{MTTF} = \int t \times f(t)\, dt = \gamma + \theta \times \Gamma\left(\frac{1 + \beta}{\beta}\right) \tag{73}$$

and the failure rate is

$$r(t) = \frac{\beta(t - \gamma)^{\beta-1}}{\theta^{\beta}} \tag{74}$$

The mean of the Weibull distribution is

$$\mathrm{Mean} = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \tag{75}$$

and the variance is

$$\sigma^2 = \theta^2\left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)\right] \tag{76}$$

77. The unconditional intensities $w(t)$ and $v(t)$ can be calculated using the following relationships (Henley and Kumamoto 1981). For the unconditional failure intensity,

$$w(t) = f(t) + \int_0^t f(t - u)v(u)\ du \tag{77}$$

and for the unconditional repair intensity

$$v(t) = \int_0^t g(t - u)w(u)\ du \tag{78}$$

These intensities can be determined using either iterative numerical integration or Laplace transform techniques when $f(t)$ and $g(t)$ are known. The unavailability for the whole process can be expressed as

$$Q(t) = W(0,t) - V(0,t) \tag{79}$$

$$Q(t) = \int_0^t [w(u) - v(u)]\ du \tag{80}$$

The conditional failure intensity can be expressed as

$$\lambda(t) = \frac{W(t)}{1 - Q(t)} \tag{81}$$

and the conditional repair intensity is expressed as

$$u(t) = \frac{v(t)}{Q(t)} \tag{82}$$

Data Requirements and Availability

78. Data requirements for application of the various failure density functions usually include a determination of the MTTF , MTTR , and any associated preventative maintenance requirements. Unfortunately, detailed data of this nature usually are not readily available. Most of the data collected on the reliability of mechanical equipment have been for aircraft or nuclear power systems, which have substantially more stringent design, manufacturing, and maintenance standards than similar equipment installed by water utilities. The most comprehensive set of reliability data for equipment of similar design and service to that found in water utilities appears to have been developed by Shultz and Parr (1981) for EPA. Among other items of equipment, Shultz and Parr collected reliability data on pumps, motors, controls, power transmission, and valves. Reliability and maintainability data as collected by Shultz and Parr (1981) are presented in Tables 5-7. Although the reported MTBF values appear high and corresponding MTTR values appear low, Shultz reported that many units operated for up to 10 years without failure. In addition, the time to repair value is based upon the active man-hours required to disassemble, correct, and reassemble the unit. Time expended waiting for materials and manpower scheduling was not included. Obviously, these items could have a significant impact on the MTTR value.

79. The data collected by Shultz and Parr (1981) were compared with reliability data on similar subsystems available from two other sources: Reliability Analysis Center (1981) and Southwest Research Institute (1978). The results of this comparison are presented in Table 8. For most subsystems, the other data bases contained substantially more operating hours than did the Shultz and Parr survey. For all subsystems, the Shultz and Parr data reflect the lowest MTBF . This result is expected since the subsystems reported in the nuclear plant reliability data system (Southwest Research Institute 1978) are all in the safety class of the nuclear steam supply system. In addition, many of the components from the nonelectric parts reliability data (Reliability Analysis Center 1981) were qualified to military specifications and were used in military applications. The added safety and/or reliability requirements for components in these types of application probably contributed to the higher MTBF values.

Stress-Strength Analysis

80. Strength of a component is defined as the ability of the component to accomplish its required mission satisfactorily without a failure when subjected to an external stress. Stress is the loading of the component, which may be mechanical load, environment, flow rate, temperature, etc. The stress (load) tends to produce failure of the component. When the strength of the component is less than the stress imposed on it, the failure occurs. This type of analysis can be applied to the reliability analysis of components of water distribution systems.

Static reliability models

81. The reliability of a hydraulic system is defined as the probability of the strength or resistance y exceeding the stress or loading x, i.e., the probability of survival. The terms "stress" and "strength" are more meaningful to structural engineers, whereas the terms "loading" and "resistance" are more descriptive to water resources engineers. The risk of a hydraulic component, subsystem, or system is defined as the probability of the loading exceeding the resistance, i.e., the probability of failure. The mathematical representation of the reliability R and the risk $\bar{R}$ can be expressed as, respectively,

$$R = P_r(y > x) = P_r(y - x > 0) \tag{83}$$

and

$$\bar{R} = P_r(y < x) = P_r(y - x < 0) \tag{84}$$

in which $P_r(\ )$ refers to probability. The relationship between reliability and risk is

$$R = 1 - \bar{R} \tag{85}$$

82. The resistance of a hydraulic structure is essentially the capacity of the structure and the loading is essentially the magnitude of flows through or over the structure, e.g., from a hydrologic event. Since the loading and resistance are random variables due to the various hydraulic and hydrologic

uncertainties, a knowledge of the probability distributions of y and x is required to develop risk and reliability models. The computation of risk and reliability can be referred to as "loading resistance interference" as shown in Figure 8. The intersection of the load resistance curves demonstrates the interaction of two composite stochastic processes. The reliability is the probability that the resistance is greater than the loading for all possible values of the loading.

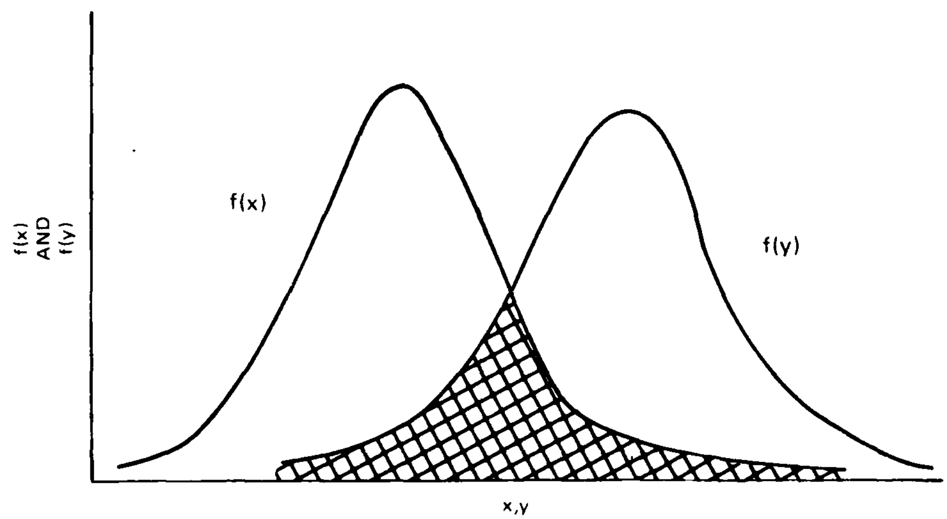

Figure 8. Typical load-resistance interference diagram

83. The word "static," from the reliability computation point of view, represents the worst single stress, or load, applied. The loading applied to many hydraulic structures is random variable, and, in addition, the number of times of loading is unknown and random. If the distribution of the loading and resistance is known, the reliability computation is referred to as a load-resistance interference diagram (Figure 8). Following the definitions given in Equations 83 and 84, the reliability and risk of a hydraulic structure can be expressed as, respectively

$$R = \int_0^{\infty} f_y(y) \left[\int_y^{\infty} f_x(x)\ dx \right] dy \qquad (86)$$

and

$$\bar{R} = 1 - \left\{ \int_0^\infty f_y(y) \left[\int_y^\infty f_x(x) \; dx \right] dy \right\} \tag{87}$$

in which $f_y(\ )$ and $f_x(\ )$ represent the probability density functions of resistance and loading, respectively. The reliability computations for a hydraulic structure for the static case require the probability distributions of loading and resistance. The safety factor SF is defined as

$$SF = \frac{\bar{Y}}{\bar{x}} \tag{88}$$

in which the bar denotes the mean. This type of SF has been referred to as a characteristic SF by Yen (1978).

84. In cases in which both the stress x and the strength y are exponentially distributed, i.e.

$$f_x(x) = \lambda_x e^{-\lambda_x x} \tag{89}$$

$$f_y(x) = \lambda_y e^{-\lambda_y y} \tag{90}$$

then the static reliability reduces to (Kapur and Lamberson 1977)

$$R = \frac{\lambda_x}{\lambda_y + \lambda_x} \tag{91}$$

85. In cases in which both the stress x and strength y are log-normally distributed, the reliability is computed as (Kapur and Lamberson 1977)

$$R = \int_{-z}^{+z} \phi(z)\ dz \tag{92}$$

where $\phi(z)$ is the probability density function for the standard normal deviate z given as

$$z = -\frac{\ln_y - \ln_x}{\sqrt{\sigma^2_{\ln_y} + \sigma^2_{\ln_x}}} \tag{93}$$

86. In cases in which the stress x is exponentially distributed and the strength is normally distributed, the reliability can be expressed as (Kapur and Lamberson 1977)

$$R = 1 - \phi\left(-\frac{\mu_y}{\sigma_y}\right) - \exp\left[-\tfrac{1}{2}\left(2\mu_y\lambda_x - \lambda_x^2\sigma_y^2\right)\right] \left[1 - \phi\left(-\frac{\mu_y - \lambda_x\sigma_y^2}{\sigma_y}\right)\right] \tag{94}$$

Dynamic reliability models

87. Dynamic or time-dependent reliability models consider repeated application of loading and also can consider the change of the distribution of resistance with time. The practical motivation behind considering time-dependent risk and reliability models is that, for hydraulic structures, there is uncertainty about the loading and resistance random variables with respect to time and loading cycles.

88. Repeated loadings on a hydraulic structure are characterized by the time each load is applied and the behavior of time intervals between the application of loads. From a reliability theory viewpoint, the uncertainty about the loading and resistance variables may be classified into three categories: deterministic, random fixed, and random independent (Kapur and Lamberson 1977). For the deterministic category, the variable assumes values that are exactly known a priori. For the random fixed case, the randomness

varies in time in a known manner. For the random independent case, the variable is not only random but the successive values assumed by the variable are statistically independent.

89. The objective of the reliability computations for the dynamic models is to determine the reliability after n cycles or occurrences of loading R_n, i.e., the probability of not having a failure on any one of the n cycles or loadings.

90. Reliability computations for dynamic (time-dependent) models can be made for deterministic and random cycle times. The loading on water distribution systems can be deterministic under normal loading conditions and random under emergency loading conditions. The model for deterministic cycles will be developed which naturally leads to the model for random cycle times. For deterministically known cycle times, the reliability at time t, $R(t)$, can be determined from the reliability after n cycles or occurrences of loading R_n as

$$R(t) = R_n; \; t_n \le t \le t_{n+1}; \qquad n = 1,2 \tag{95}$$

and

$$R = R^n \tag{96}$$

in which t_n = the instant in time at which the nth cycle occurs. Referring to the loading as x and the resistance as y, R_n can be expressed as

$$R_n = P[(x_1 < y) \cap (x_2 < y) \cap \ldots \cap (x_n < y)] \tag{97}$$

$$R_n = P[(\max(x_1, x_2 \ldots x_n) < y] \tag{98}$$

By letting the maximum loading, $x_{max} = \max(x_1, x_2 \ldots x_n)$, the distribution $F_n(x)$ of x_{max} is

$$F_n(x) = [F_x(x)]^n \tag{99}$$

provided the loadings are independent and identically distributed, in which $F_x(x)$ is the cumulative distribution of the loadings or hydrologic events which is determined from integrating the probability density function of the loadings.

91. For the time-dependent reliability model for deterministic cycles, the reliability is expressed as

$$R_n = \int_o^\infty f_y(y) \left[\int_o^y f_x(x)\ dx \right]^n dy = \int_o^\infty f_y(u) [F_x(y)]^n\ dy \tag{100}$$

The preceding reliabilities for random loading times can be expressed in terms of time as

$$R(t) = \int_{n=0}^{\infty} \pi_n(t) R_n \tag{101}$$

where

$\pi_n(t)$ = probability of n loadings occurring in the time interval [0,t]

R_n = probability of all n successes

It is now evident that the case of deterministic cycle times is a special case of the preceding reliability equation for random cycle times.

92. A Poisson distribution can be used to describe the probability of the number of events occurring in a given time interval, given as

$$\pi_n(t) = \frac{e^{-\alpha t}(\alpha t)^n}{n!} \tag{102}$$

in which α = the mean rate of occurrence of the loading which may be estimated from historical data. For example, if annual data are being used, $\alpha = 1/T_r$ in which T_r is the return period. The mean and variance are both at where t can be considered as the expected service life of the hydraulic structure. Other distributions may also be applicable but they lead to more complicated analysis.

93. For the random independent loading and random fixed resistance, the time-dependent reliability can be expressed as:

$$R(t) = \sum_{n=0}^{\infty} \frac{e^{-\alpha t}(\alpha t)^n}{n!} \int_0^{\infty} f_y(y) \left[\int_0^{y} f_x(x)\ dx \right]^n dy$$

$$= \int_0^{\infty} f_y(y) e^{-t[1-F_x(y)]}\ dy \qquad (103)$$

94. For random independent loading and random fixed resistance, R for one loading cycle is expressed by Equation 86 and $R(t)$ is expressed by Equation 101. Thus, using the Poisson distribution, Equation 102, the reliability is expressed as

$$R(t) = \sum_{n=0}^{\infty} \frac{e^{-\alpha t}(\alpha t)^n}{n!} R^n = e^{-\alpha t(1-R)} \qquad (104)$$

95. A computer program for computing risk-SF curves for the dynamic case has been developed by Tung and Mays (1980) which can consider various distributions such as normal, lognormal, extremal type I, Pearson type III, log-Pearson type III, and Weibull distribution loading.

PART IV: SYSTEM RELIABILITY ANALYSIS

Simple Systems

96. Most systems are composed of several subsystems. The reliability of the system depends on how the components are interconnected. Several methods for computing system reliability are presented below.

Series systems

97. The simplest type system is a series system in which every component must function if the system is to function. Considering the random variable of the time of failure as t_i for the i-th component, then for a system of n components, the system reliability is

$$R_s(t) = \prod_{i=1}^{n} P(t_i > t) = \prod_{i=1}^{n} R(t) = (R_1)(R_2)\ldots(R_n) \qquad (105)$$

where $R_i(t)$ is the reliability for the i-th component. For a system that has failure times exponentially distributed (with constant failure rates) so that the i-th component reliability is $e^{-\lambda_i t}$ then the system reliability is

$$R_s(t) = \exp\left(- \sum_{i=1}^{n} \lambda_i t\right) \qquad (106)$$

The MTTF is

$$\mathrm{MTTF} = \int_0^{\infty} \exp\left(-\Sigma\lambda t \ dt\right) = \frac{1}{\sum_{i=1}^{n} \lambda_i} \qquad (107)$$

As an example of the series system, consider two different pumps in series, both of which must operate to pump the required quantity. The constant failure rates for the pumps are $\lambda_1 = 0.0003$ failures/hr and $\lambda_2 = 0.0002$ failures/hr . For a 2,000-hr mission time, the system reliability is:

$$R_s(t) = e^{-(0.0003+0.0002)(2000)} = 0.90484 \qquad (108)$$

and the MTTF is

$$MTTF = \frac{1}{0.0003 + 0.0002} = 2,000 \text{ hr} \tag{109}$$

Chain series system

98. A series chain model is a series system such that if any one component fails, the system will fail. This model is based on the idea of a chain composed of n links where the chain will break if the applied stress x exceeds the strength y of any one link. This model is also referred to as a weakest link model. The system reliability is then

$$R_s = \min_i R_i \tag{110}$$

The reliability for any one link is

$$R_i = P(x > y) = \int_0^\infty \int_y^\infty f_x(x) f_y(y) \, dy \, dx \tag{111}$$

where

$f(x)$ = probability distribution function for the strength

$f(y)$ = probability distribution function for the stress

Parallel system

99. A parallel system is defined as one which will fail if and only if all units in the system fail or malfunction. The pure parallel system is one in which all components are initially activated, and any component can maintain the system operation. The system reliability is then expressed as

$$R_s(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \tag{112}$$

For a system with exponentially distributed time to failure and a constant failure rate for each component of the system, the system reliability is

$$R_s(t) = 1 - \prod_{i=1}^{n} (1 - e^{-\lambda_i t}) \tag{113}$$

and the MTTF for a system with identical components is

$$\text{MTTF} = \frac{1}{\lambda} \sum_{i=1}^{n} \frac{1}{i} \tag{114}$$

As an example of a parallel system, consider two identical pumps operating in a redundant configuration so that either pump could fail and the peak discharge could still be delivered. Both pumps have a failure rate of $\lambda = 0.0005$ and both pumps start operating at $t = 0$. The system reliability for a mission time of $t = 1{,}000$ hr is

$$R_s(t) = 2e^{-\lambda t} - e^{-2\lambda t} = 2e^{-(0.0005)(1000)} - e^{-2(0.0005)(1000)}$$
$$= 1.2131 - 0.3679 = 0.8452 \tag{115}$$

The MTTF is

$$\text{MTTF} = \frac{1}{\lambda}\left(\frac{1}{1} + \frac{1}{2}\right) = \frac{3}{2}\,\frac{1}{\lambda} = 1.5\left(\frac{1}{0.0005}\right) = 3{,}000 \text{ hr} \tag{116}$$

Standby redundancy

100. A standby redundant system is a parallel system in which only one component or subsystem is in operation. If the operating component fails, then another component is operated. This type of system is different than the parallel network where all the components are operating because standby units do not operate. The system reliability for a system with $n + 1$ components in which one component is operating and n units are on standby until the operating unit fails, is given by

$$R_s(t) = \sum_{i=o}^{n} \frac{(\lambda t)^i e^{-\lambda t}}{i!} \tag{117}$$

This assumes the following: the switching arrangement is perfect, the units are identical, the component failure rates are constant, the standby units are as good as new, and the unit failures are statistically independent. For $n + 1$ nonidentical components with different failure time density functions, the system reliability is

$$R_s(t) = \int_t^{\infty} f_{st}(t)\, dt \tag{118}$$

where $f_{st}(t)$ is the standby redundant system failure density given by

$$f_{st}(t) = \int_o^t \int_o^{y_n} \cdots \int_o^{y_2} f_1(y_1) f_2(y_2 - y_1) \cdots f_{n+1}(t - y_n)\, dy_1\, dy_2 \cdots dy_n \tag{119}$$

As an example of a standby redundant system, assume an exponential failure distribution and consider two identical pumps, one operating and the second on standby, with identical failure rates of $\lambda = 0.0005$ failures/hr. The standby unit is as good as new at time $t = 0$. The system reliability for $t = 1{,}000$ hr is

$$R_{st}(t) = (1 + \lambda t)e^{-\lambda t} = (1 + 0.0005)e^{-(0.0005)(1000)} = 0.6068 \tag{120}$$

101. A k-out-of-n system is a system in which a specified number of subsystems must be good for system success. The binomial distribution is used to define the system reliability for k-out-of-n of independent and identical units given by

$$R_{k/n} = \sum_{i=k}^{n} \binom{n}{i} R^i (1 - R)^{n-i} \tag{121}$$

where $\binom{n}{i} = \frac{n!}{i!(n - i)!}$

For a constant failure rate the reliability is expressed as

$$R_{k/n}(t) = \sum_{i=1}^{n} \binom{n}{i} (e^{-\lambda t})^i \frac{(1 - e^{-\lambda t})^n}{(1 - e^{-\lambda t})^i} \tag{122}$$

As an example of a k-out-of-n system, consider a pumping system with three pumps, one of which is standby, all with constant failure rates of $\lambda = 0.0005$ failures/hr. The system reliability for $t = 1{,}000$ hr is

$$\begin{aligned} R_{2/3}(t) &= 3e^{-(2)(0.0005)(1000)} - 2e^{-(3)(0.0005)(1000)} \\ &= 1.1036 - 0.4463 = 0.6573 \end{aligned} \tag{123}$$

Complex Systems

102. As shown in the previous section, the reliability of series-parallel systems is generally straightforward. In most practical situations, such as water distribution systems, the system (network) has a nonseries-parallel configuration and the evaluation is much more difficult. There have been many techniques developed for system reliability evaluation. A great deal of work has been done on state enumeration methods (event-space methods), network reduction methods, and path enumeration methods. A brief summary is provided of each of these methods.

State enumeration methods

103. This method lists all possible mutually exclusive states of the system. A state is defined by listing the successful and failed elements in the system. For a system with n elements or components, in general there are 2^n states, so that a system with 10 components would have 1,024 states. The states which result in successful system operation are identified and the probability of occurrence of each successful state is computed. The last step is to sum all the successful state probabilities which give the system reliability. This method can be computationally infeasible for systems having a large number of components (Brown 1971).

Network reduction methods

104. These methods combine the series, parallel, and series-parallel

subsystems until a nonseries-parallel system which cannot be further reduced is obtained. Factoring theorems are then used to obtain system reliability. A component A is selected, and two networks are obtained and generated when A is replaced by a short-circuit (perfect competition) and an open circuit. If the two networks are simple series-parallel, they can be reduced; otherwise, the next block A must be selected and the procedure is repeated. Further discussions of network reduction methods can be found in Moscowitz (1958), Buzacott (1970), Banerjee and Rajamani (1972), and Misra (1972).

<u>Path enumeration methods</u>

105. Path enumeration methods are very valuable tools for system reliability evaluation. A path is a set of elements (components) which form a connection between input and output when traversed in a stated direction. A minimal path is one in which no node is traversed more than once in going along the path. The i-th minimal path will be denoted as P_i , $i = 1...m$. Assuming any path is operable, the system performs adequately, then the system reliability is

$$R = P_r\left[\bigcup_{i=1}^{m} P_i\right] \tag{124}$$

where P_r [ ] represents probability and $\bigcup$ denotes the union.

106. A cut set is defined as a set of elements, which if it fails, causes the system to fail regardless of the condition of the other elements in the system. A minimal cut is one in which there is no proper subset of elements whose failure alone will cause the system to fail. In other words a minimal cut is such that if any component is removed from the set, the remaining elements collectively are no longer a cut set. The minimal cut sets are denoted as C_i , $i = 1...m$ and $\bar{C}_i$ denotes the complement of C_i , i.e. the failure of all elements of the cut C_i . The system reliability is

$$R = 1 - P_r\left[\bigcup_{j=1}^{m} \bar{C}_j\right] \tag{125}$$

107. A basic algorithm for the path enumeration method can be stated as (Henley and Gandhi 1975):

a. Find all minimal paths using the reliability graph. Several computer codes have been developed for this purpose which are discussed in a later section.

b. Find all required unions of the paths.

c. Give each path union a reliability expression in terms of module reliability.

d. Use the following equation expressing the system reliability in terms of module reliabilities.

$$R = \sum_{i=1}^{m} \prod_{l \in P_i} R_l - \sum_{i=1}^{m} \sum_{j>i}^{m} \prod_{l \in P_i \cup P_j} R_l + \sum_{i=1}^{m} \sum_{j>i}^{m} \sum_{k>j}^{m} \prod_{l \in P_i \cup P_j \cup P_k} R_l + \cdots + (-1)^{m-1} \prod_{l \in \bigcup_{i=1}^{m} P_i} R_l \tag{126}$$

where the members of the i-th path are denoted as $l \in P_i$, the union of the i-th and j-th paths are denoted by $l \in P_i \cup P_j$, etc.

Review of system reliability evaluation techniques for complex systems

108. Hwang, Tillman, and Lee (1981) presented a review of literature related to system reliability evaluation techniques for small to large complex systems. A large system was defined as one which has more than ten components and a moderate system as one which has more than six components and less than ten. Complex systems were defined as ones which could not be reduced to a series-parallel system.

109. Hwang, Tillman, and Lee concluded that for a large complex system computer programs should be used that provide the set of minimal cuts and calculate the minimal cut approximation to system reliability. Minimal paths can be generated from minimum cuts. Based on minimal path (cut) sets, reliability approximations can then be obtained for large complex networks. Hwang, Tillman, and Lee also noted that Monte Carlo methods for system reliability evaluation were used when component reliabilities are sampled by the Monte Carlo method. Hwang, Tillman, and Lee also identified several miscellaneous approaches for evaluating complex systems including a moment method, a block

diagram method, Bayesian decomposition, and decomposition by Boolean expression.

110. Hwang, Tillman, and Lee (1981) concluded that of all the evaluation techniques in the papers surveyed only a few had limited success in solving some large complex system reliability problems and few techniques have been completely effective when applied to large system reliability problems. They felt that a new direction should be to develop a generally efficient graph partitioning technique for reliability evaluation of large, highly interconnected networks.

111. Since the 1981 paper of Hwang, Tillman, and Lee, several other system reliability evaluation techniques have been reported in the literature. Aggarwal, Chopra, and Bajwa (1982) presented a method that uses decomposition of a probabilistic graph using cut sets. The method is applied to a simplified network with five nodes and seven links and only limited computational results are presented.

112. Bennetts (1982) presents a method for the analysis of reliability block diagrams using Boolean algebra techniques. The method is based on an analysis of path sets derived from reliability block diagrams. Boolean methods are applied to each path so that the component reliability parameters are considered to be Boolean variables rather than probabilistic variables and the whole problem is treated in a Boolean framework. Hagstrom (1983) presents a model using decomposition trees of a network based upon finding and analyzing triconnected components of the network.

113. Deuermeyer (1982) presented an interesting approach to network reliability analysis of flow networks that is based upon developing network functions. A network function specifies the maximum flow deliverable by the network while in a specific state. The maximum flow problem can be represented as a linear programming problem in which the objective is to maximize flow. The probability distribution of maximum flow can then be determined and used as an index of reliability.

114. Touey (1983) presented a new algorithm for computing network terminal reliability from a set of paths or cut sets. This algorithm is based on selective generation of relevant states by way of methods for choosing and pruning branches of a binary tree. The author states that the method is easy to implement and to understand, and has proven in practice to be more efficient than the fastest methods published.

Multistate systems
with multi-state components

115. Hudson and Kapur (1982) present models for reliability analysis to systems which can have a range of states and all of its components can also have a range of multiple states. Such systems generally have various levels of operational performance so that the total system effectiveness measures reflect all the performance levels and their reliabilities. Binary system theory requires that each component, as well as the entire system, be considered either functioning or failed. Multistate approaches allow states of partial failure for both the system and its components. The advantage is that either standby or active redundancy can be considered. The methodology presented in Hudson's and Kapur's paper is illustrated by a simple example of a domestic hot water system consisting of components representing a gas fired subsystem, a solar collector-controller, two pumps, and a solar piping and storage subsystem.

116. This type of approach seems to be in the developmental stages and may be a little premature for application to water distribution systems. However, once the technology is developed, this should prove to be very promising. Earlier work on the multistate (discrete state) point of work was reported by Dhillon (1975), Murchland (1975), Barlow and Wu (1978), and El-Neweihi, Proschan, and Sethuraman (1978).

Fault Tree Analysis

117. Fault tree analysis has been proposed as a method for evaluating the reliability of systems. A fault tree is a logical diagram representing the consequences of the component failures (basic or primary failures) on system failure (top failure). Dhillon and Singh (1981) defined the advantages and disadvantages of the fault tree analysis technique. Advantages include:

a. Provides insight into the system behavior.

b. Requires the reliability analyst to understand the system thoroughly and deal specifically with one particular failure at a time.

c. Helps to ferret out failures deductively.

d. Provides a visibility tool to designers, users, and management to justify design changes and trade-off studies.

e. Provides options to perform quantitative or qualitative reliability analysis.

f. Technique can handle complex systems more easily.

Disadvantages include:

a. Can be costly and time-consuming.

b. Results can be difficult to check.

c. Technique normally considers that the system components are in either working or failed state; therefore, the partial failure states of components are difficult to handle.

d. Analytical solution for fault trees containing standbys and repairable components are difficult to obtain for the general case.

e. To include all types of common-cause failure requires considerable effort.

118. Another advantage not mentioned by Dhillon and Singh (1981) is that commercial codes are available to perform the analysis.

Fault tree construction

119. Before constructing a fault tree, the analyst must thoroughly understand the system and its intended use. One must determine the higher order functional events and continue the fault event analysis to determine their logical relationship with lower level events. Once this is accomplished, the fault tree can be constructed. A brief description of fault tree construction is presented below. The basic concepts of fault tree analysis are presented in Henley and Kumamoto (1981) and Dhillon and Singh (1981).

120. The major objective of fault tree construction is to represent the system condition, which may cause system failure, in a symbolic manner. In other words the fault tree consists of sequences of events that lead to the system failure. These sequences of events are represented by AND, OR, or other logic gates. There are actually two types of building blocks: gate symbols and event symbols.

121. Gate symbols connect events according to their casual relation such that they may have one or more input events but only one output event. Table 9 lists the various gate symbols (Henley and Kumamoto 1981). The AND gate denotes that an output event occurs if and only if all the input events occur. The OR gate is an intermediate event which denotes that there is no output unless one and only one of the input events occurs. The priority AND gate is logically equivalent to an AND gate with the exception that the input events must occur in a specific order. The inhibit gate produces output only

when the conditional input is satisfied and is logically equivalent to an AND gate with two input events.

122. Event symbols are shown in Table 10. A fault event, denoted by a rectangular box, results from a combination of more basic faults acting through logic gates. A circle denotes a basic component failure that represents the limit of resolution of a fault tree. A diamond represents a fault event whose causes have not been fully developed. The house-shaped event denotes a fault event which is expected to occur. A triangle denotes a transfer IN or OUT and is used to avoid repeating sections of the fault tree.

123. There are two approaches, forward analysis and backward analysis, for analyzing causal relations. Forward analysis starts with a set of failure events and proceeds forward, looking for possible consequences resulting from the events. The backward analysis, which is used in fault tree analysis, begins with a system hazard (failure) and traces backward, searching for possible causes of the hazard.

124. Henley and Kumamoto (1981) present heuristic guidelines for constructing fault trees which are summarized in Table 11 and Figure 9 and are listed on the following page:

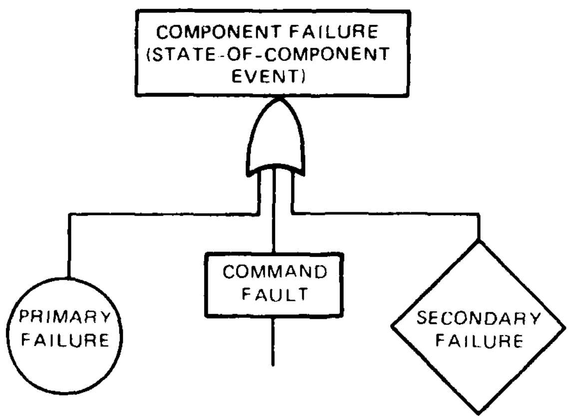

Figure 9. Development of a component failure or state-of-component event (Henley and Kumamoto 1981). Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J., Reliability Engineering and Risk Assessment, 1981, p 71

a. Replace abstract events by less abstract events.

b. Classify an event into more elementary events.

c. Identify distinct causes for an event.

d. Couple trigger event with "no protection actions."

e. Find cooperative causes for an event.

f. Pinpoint component failure events.

g. Develop component failure using Figure 9.

125. An example of a fault tree construction is given for the system in Figure 10. In this pumping system, the tank is filled in 10 min and empties in 50 having a cycle time of 60 min. After the switch is closed, the time is set to open the contacts in 10 min. If the mechanism fails then the horn sounds and the operator opens the switch to prevent pressure tank rupture. The fault tree for the pumping system is shown in Figure 11.

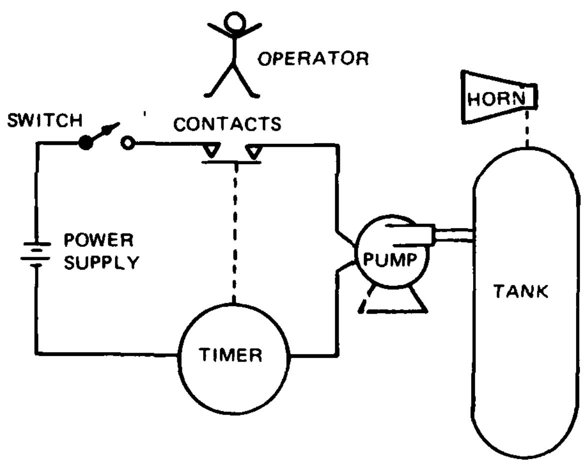

Figure 10. Schematic diagram of a pumping system (Henley and Kumamoto 1981). Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J., Reliability Engineering and Risk Assessment, 1981, p 72

Evaluation of fault trees

126. The basic steps used to evaluate fault trees include:

a. Construct the fault tree.

b. Determine the minimal cut sets.

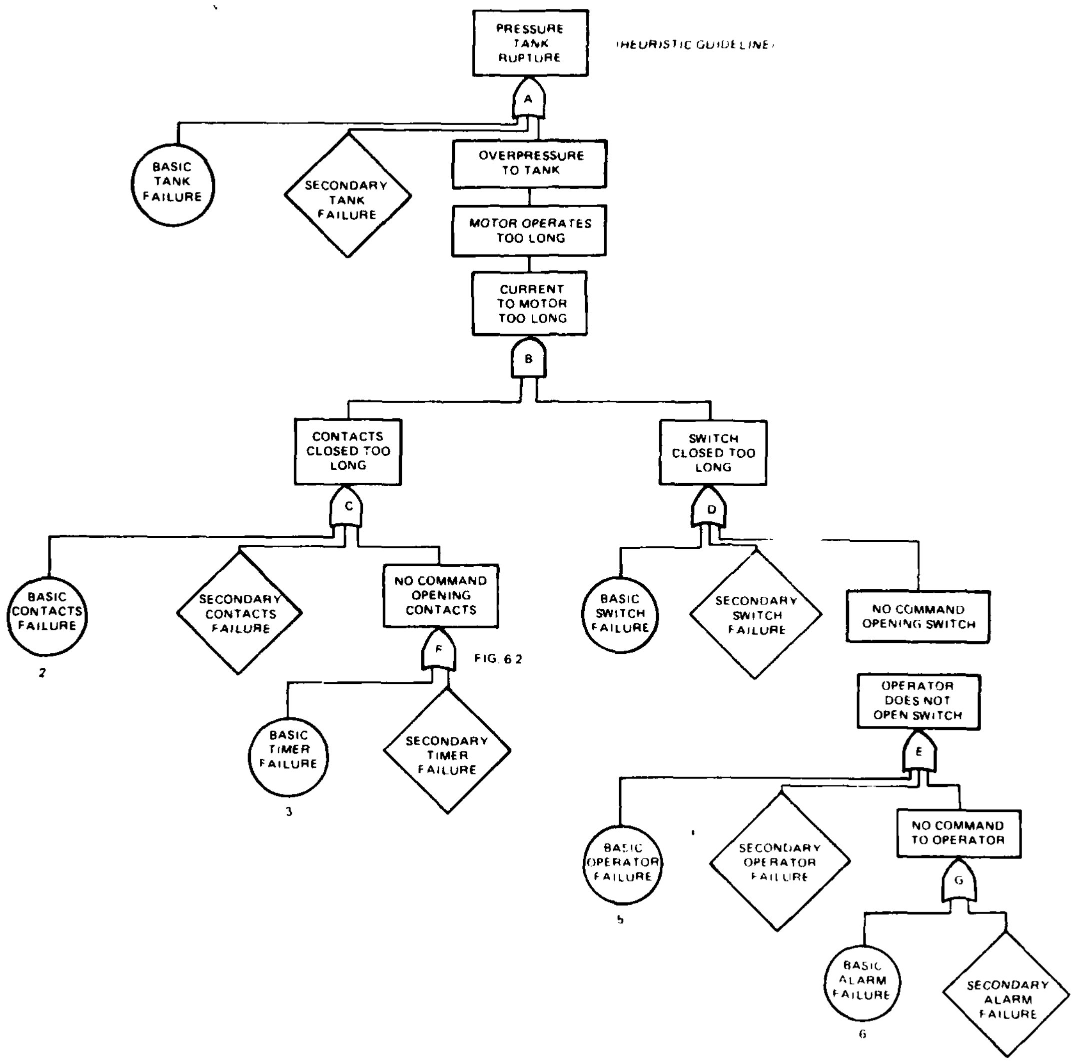

Figure 11. Fault tree for pumping system shown in Figure 10 (Henley and Kumamoto 1981). Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J., Reliability Engineering and Risk Assessment, 1981, p 73

c. Develop primary event information.

d. Develop cut set information.

e. Develop top event information.

127. In order to evaluate the fault tree, one should always start from the minimal cut sets which in essence are critical paths. Basically, the fault tree evaluation comprises two distinct processes: (a) the determination of the logical combination of events that cause top event failure expressed in

minimal cut sets and (b) the numerical evaluation of the expression.

128. Cut sets are collections of basic events such that if all these basic events occur, then the top event is guaranteed to occur. The path set is a dual concept to the cut set in that it is a collection of basic events, and if none of the events in the set occur, then the top event is guaranteed to not occur. As one could imagine, a large system has an enormous number of failure modes. A minimal cut set is one that if any basic event is removed from the set then the remaining events collectively are no longer a cut set. By the use of minimal cut sets, the number of cut sets and basic events are reduced in order to simplify the analysis. Several computer codes are available for generating cut sets including MOCUS (Fussell, Henry, and Marshall 1974) which was developed to obtain minimal cut sets from fault trees. A list of available computer codes for reliability analysis is found in Appendix B.

129. The system availability $A_s(t)$ is the probability that the top event does not exist at time t, which is the probability of the systems operating successfully when the top event is an OR combination of all system hazards. System unavailability $Q_s(t)$ is the probability that the top event exists at time t, which is either the probability of system failure or the probability of a particular system hazard at time t. The system availability and system unavailability are complementary, i.e.

$$A_s(t) + Q_s(t) = 1 \tag{127}$$

130. System reliability $R_s(t)$ is the probability that the top event does not occur over time interval $(0,t)$. System reliability requires continuation of the nonexistence of the top event and the following holds

$$R_s(t) \le A_s(t) \tag{128}$$

131. The system unreliability $F_s(t)$ is the probability that the top event occurs before time t and is complementary to the system reliability

$$R_s(t) + F_s(t) = 1 \tag{129}$$

and

$$F_s(t) \geq Q_s(t) \tag{130}$$

The system failure density $F_s(t)$ is defined as

$$f(t) = \frac{dF_s(t)}{dt} \tag{131}$$

132. System conditional failure intensity $V_s(t)$ is the probability that the top event occurs per unit time at time t given that it does not exist at time t. The system unconditional failure intensity $W_s(t)$ is the probability that the top event occurs per unit time at time t. The expected number of top events during time interval $(t,t+dt)$ is

$$W_s(t,t+dt) = \int_t^{t+dt} w_s(t)\ dt \tag{132}$$

133. The mean time to first failure is the expected length of time to the first occurrence of the top event and is given by

$$MTTF_s = \int_o^{\infty} tf_s(t)\ dt \tag{133}$$

134. Considering independent basic events $B_1 \ldots B_n$, the probability of a cut set occurrence at time $t, Q^*(t)$ is obtained from the intersection of the basic events as

$$Q^*(t) = P_r(B_1 \cap B_2 \cap \ldots \cap B_n) = \prod_{j=1}^{n} Q_j(t) \tag{134}$$

where n is the number of cut set members and $Q_j(t)$ is the probability of the j-th basic event existing at time t. A cut set occurrence is when all basic events in the cut set are occurring. The asterisk * is used to denote that the quantity is a cut set. The notation $Q(t)$ refers to a component unavailability, $Q^*(t)$ refers to the cut set unavailability, and $Q_s(t)$ refers to the system unavailability.

135. The probability of occurrence of a cut set per unit time at time t given no cut set failure at time t is denoted as $\lambda^*(t)$. The probability that the cut set occurs during the time interval $(t,t+dt)$ is

$$\lambda^*(t)\ dt = P[C^*(t,t+dt)\ \bar{C}^*(t)] = \frac{P_r[C^*(t,t+dt)]}{\bar{P}[C^*(t)]} \tag{135}$$

where

$C^*(t,t+dt)$ = occurrence of the cut set during $(t,t+dt)$

$C^*(t)$ = the nonexistence of the cut set failure at time t

Henley and Kumamoto (1981) show that the numerator is $W^*(t)\ dt$ so that

$$\lambda^*(t)\ dt = \frac{\sum_{j=1}^{n} w_j(t)\ dt \prod_{\substack{k=1\\k=j}} Q\ (t)}{1 - Q^*(t)} \tag{136}$$

Each term in the summation is the probability of the j-th basic event during $(t,t+dt)$ with the remaining basic event existing at time t . The denominator is the probability of the nonexistence of the cut set failure at time t .

136. The term $W^*(t)$ is the expected number of times the cut set occurs per unit time at time t defined as

$$W^*(t) = \sum_{j=1}^{n} w_j(t) \prod_{\substack{k=1\\k=j}}^{n} Q_k(t) \tag{137}$$

so that

$$\lambda^*(t) = \frac{w^*(t)}{[1 - Q^*(t)]} \tag{138}$$

137. Similar expressions hold for $u^*(t)$ and $v^*(t)$

$$v^*(t) = \sum_{j=1}^{n} v_j(t) \prod_{k=1}^{n} [1 - Q_k(t)] \tag{139}$$

and

$$u^*(t) = \frac{v^*(t)}{Q^*(t)} \tag{140}$$

138. The values of $W^*(0,t)$ and $V^*(0,t)$ are

$$W^*(0,t) = \int_0^t w^*(u)\, du \tag{141}$$

$$V^*(0,t) = \int_0^t v^*(u)\, du \tag{142}$$

139. Henley and Kumamoto (1981) show that the system unavailability can be determined using

$$Q_s(t) = \sum_{i=1}^{N_c} Q_i^*(t) - \sum_{i=2}^{N_c} \sum_{j=1}^{i-1} \prod_{i,j} Q(t) + \ldots$$
$$+ (-1)^{m-1} \sum_{1 \le i_1 < i_2 < \ldots < i_m \le N_c} \prod_{i_1 \ldots i_m} Q(t) \tag{143}$$
$$+ \ldots + (-1)^{N_c - 1} \prod_{i_1 \ldots i_{N_c}} Q(t)$$

where

Π = product of $Q(t)$ for the basic events in cut set i_1 or $i_2 \ldots$ or i_m

N_c = total number of minimal cuts

The lower and upper bounds for $Q_s(t)$ can be written as (Henley and Kumamoto 1981):

$$\sum_{i=1}^{N_c} Q_i^*(t) - \sum_{i=2}^{N_c} \sum_{j=1}^{i-1} \prod_{i,j} Q(t) \le Q_S(t) \le \sum_{i=1}^{N_c} Q_i^*(t) \qquad (144)$$

where Π refers to the product of cut sets i or j.

140. The expected number of times the top event occurs at time t, per unit time, is $w_s(t)$. Let e_i be the event that the i-th cut set failure occurs at time t to $t+dt$ so that $P_r(e_i) = W_i{*}(t)\ dt$. For the top event to occur in time $(t,t+dt)$, none of the cut set failures can exist at time t and one or more must fail during the time t to $t+dt$, so that

$$w_s(t)\ dt = Pr\left(A \bigcup_{i=1}^{N_c} e_i\right) \qquad (145)$$

where $A \bigcup_{i=1}^{N_c} e_i$ is $A \bigcap \left(\bigcup_{i=1}^{N_c} e_i\right)$

$\left(\bigcup_{i=1}^{N_c} e_i\right)$ = the event that one or more of the cut set failures occur at time t

A = the event of none of the cut sets failures existing at time t

This can be reduced to (Henley and Kumamoto 1981):

$$w_s(t) = w_s^{(1)}(t) - w_s^{(2)}(t) \qquad (146)$$

where

$w_s^{(1)}(t)$ = contribution from the event that one or more cut sets fail during time $(t,t+dt)$

$w_s^{(2)}(t)$ = those cases in which one or more cut sets fail during $(t,t+dt)$, while the other cut sets that have already failed to time t have not been repaired

141. Computer programs have been developed to compute system parameters (unavailability, availability, expected number of failures and repairs, and conditional failure and repair intensities) given minimal cut or path sets of large complicated fault trees. KITT-1 (Vesely and Narum 1970) applies the above concepts of kinetic tree theory. The program handles independent basic events which are either repairable or nonrepairable and have constant failure rates and constant repair rates u . Another version of the program, KITT-2, allows for time-varying failure and repair rates. A later version called KITT-1T (Ong and Henley 1980) is a modified version of KITT-1 to include time delays provided by storage tanks and component (standby) redundancy.

PART V: AVAILABILITY AND RELIABILITY OF WATER DISTRIBUTION SYSTEM COMPONENTS

Background

142. As discussed in previous parts of this report, there are a number of techniques available for evaluating the reliability of a mechanical system. Because of system complexity, these procedures have not been generally used to evaluate the reliability of water distribution systems.

143. However, simplifying assumptions can be made that enable the engineer to apply these procedures to water distribution system components. The following sections present detailed concepts for applying these procedures to water distribution system component analysis.

Pumps

144. Time to failure analysis can be applied to the evaluation of pumping systems. For the sake of simplicity, the exponential distribution is used to illustrate a procedure for the time to failure analysis of a pump in which the pump failure data are lumped, i.e. failure data for the pumps' individual subsystems are lumped into one parameter. A more detailed analysis in which the reliability and availability of the individual subsystem is presented in the following section.

145. Damelin, Shamir, and Arad (1972) presented data for a pump indicating an MTTF of 1,200 hr and a MTTR of 50 hr for a [illegible]0-m^3/hr-capacity pump. Equations 54 and 56 can be used to calculate values for failure rate λ and repair rate μ of 0.0008/hr (7.3/year) and 0.02/hr (175.2/year), respectively. Table 12 presents reliability, unreliability, and availability values for these values of λ and μ .

146. The reliability of a system is the probability that the system experiences no failures during the time interval $(0,t)$. The reliability curve for $\lambda = 0.0008$ is shown in Figure 12. The availability of a system is the probability that the system is operational at time t . For repairable systems, availability is a more appropriate measure of the probability that a system will be operational. Availability is affected by both the MTTF and

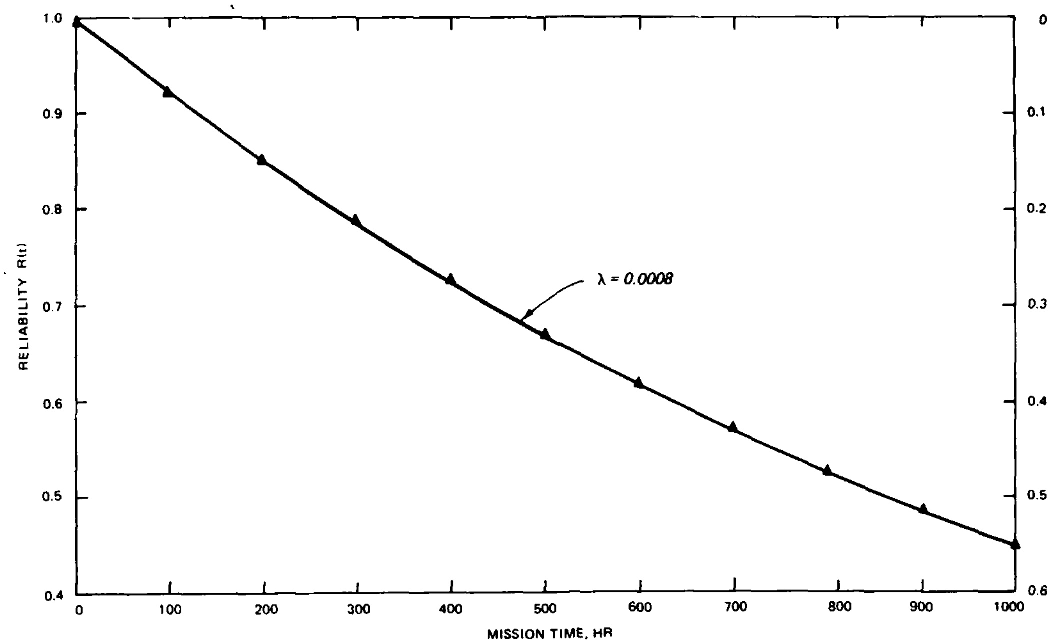

Figure 12. Reliability curve for a pump system with $\lambda = 0.0008/hr$

MTTR . Figure 13 presents availability curves for $\lambda = 0.0008/hr$ and $\mu = 0.02$, 0.01, and 0.005/hr .

147. For repairable systems, the availability is always greater than or equal to the reliability. This concept is illustrated graphically in Figure 14 for $\lambda = 0.0008/hr$ and $\mu = 0.01/hr$.

148. For repairable systems, as t approaches infinity, the availability approaches a constant value greater than 0 (stationary availability). A comparison is of the effect of both μ and λ on the stationary availability and unavailability (Figure 15).

Pumping Stations

Component description

149. Pumping stations are one of the major components of a water distribution system. A pumping station consists of one or more pumping units or systems supported by appropriate electrical, piping, and structural systems.

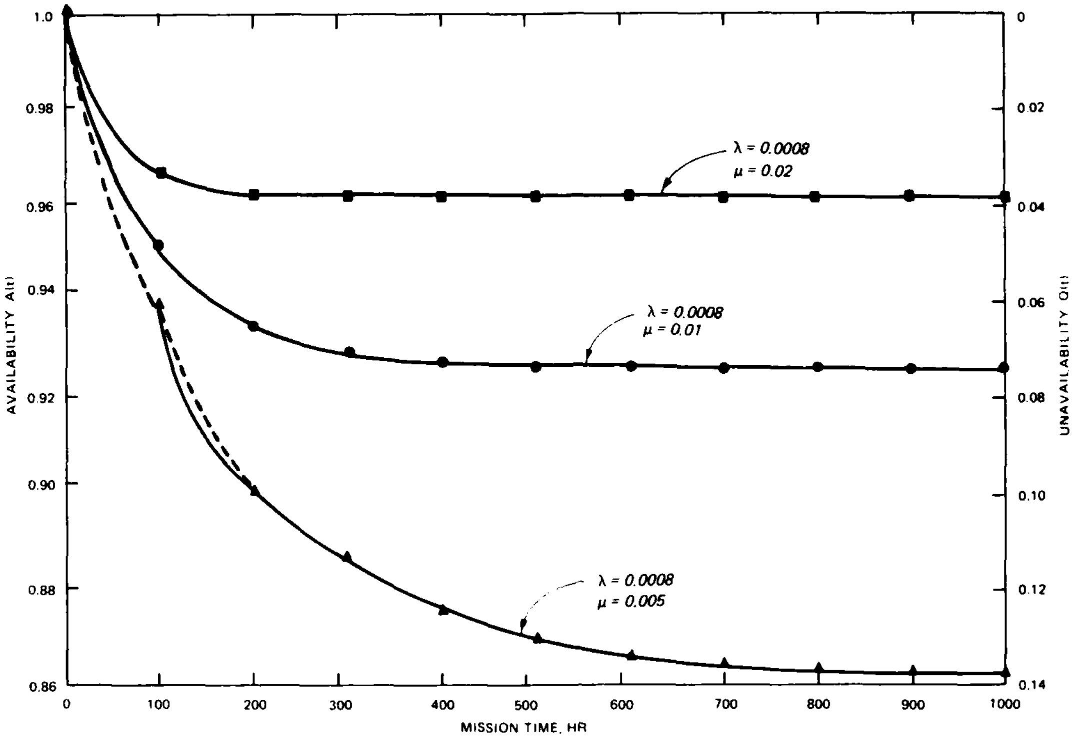

Figure 13. Availability curves for a pump system with $\lambda = 0.0008$/hr and $\mu = 0.02$, 0.01, and 0.005/hr

A typical pumping station is illustrated schematically in Figure 16. The pumping unit is the primary system within the pumping station and includes five major subsystems: pump, motor (driver), power transmission, valves, and controls. The evaluation of pumping station reliability is a three-step process incorporating the analysis of subsystem reliability, system reliability, and finally the reliability of the pumping station component of the water distribution system. The reliability and availability evaluation can be conducted to any desired level of detail for which data are available. For purposes of discussion and illustration, the evaluation technique presented below will evaluate the pumping station as being composed of four major systems: pumping system, electrical system, piping system, and structural system. The pumping system will be further divided into the above listed five major pumping unit subsystems.

Design guidance

150. A common problem in the design and operation of water treatment and distribution systems is deciding the number and sizes of pumps to be

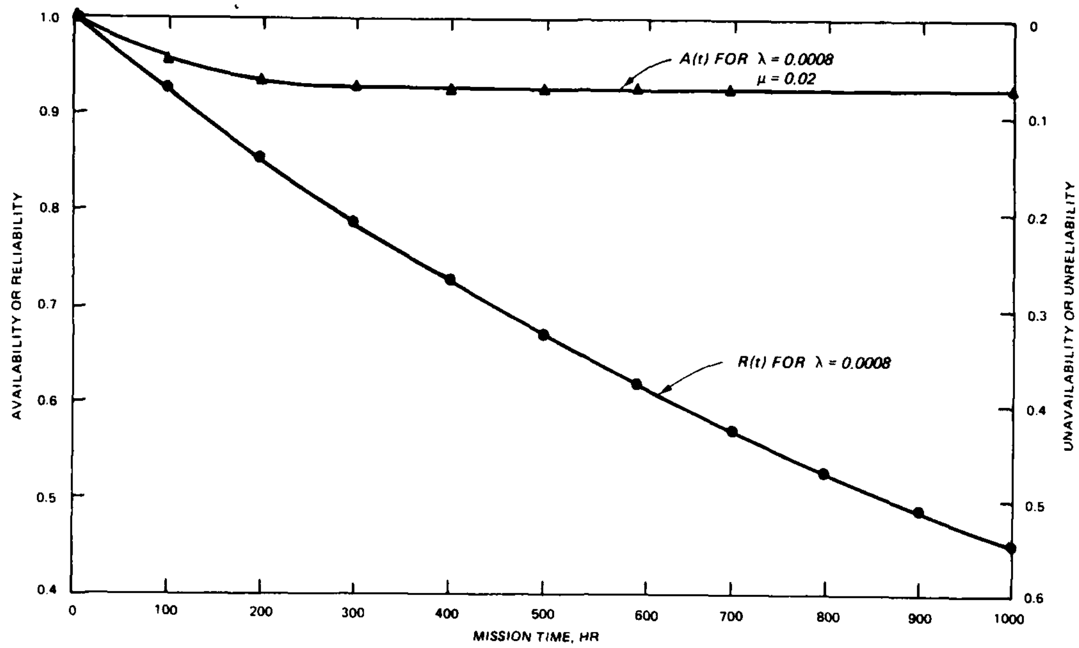

Figure 14. Comparison of reliability and availability for λ = 0.0008/hr and μ = 0.02/hr

installed in a pumping station. Traditionally, this has been accomplished using various rules of thumb or good engineering judgment. Little attention has been given to the design of pumping stations based on the concepts of system reliability or availability. The selection of the number of pumps usually depends on the size of the installation and the engineer's preference. The most common design basis is the concept of firm pumping capacity. Firm capacity is defined as the pumping capacity of the facility with the largest pump-out operation. The Great Lakes-Upper Mississippi River Board of State Sanitary Engineers (1972) requires that at least two pumping units be provided except where ample time will be available between pumping periods for necessary repairs. If only two units are provided, each unit is required to have sufficient capacity to supply the peak demand. When more than two pumping units are provided, the capacity of the pumps should be sufficient to meet peak demand with one pump out of service. Sanks (1978) suggests that the design capacity of a pumping facility be based on the maximum daily flow rate with peak hourly rates supplied from system storage. Sanks suggests use of

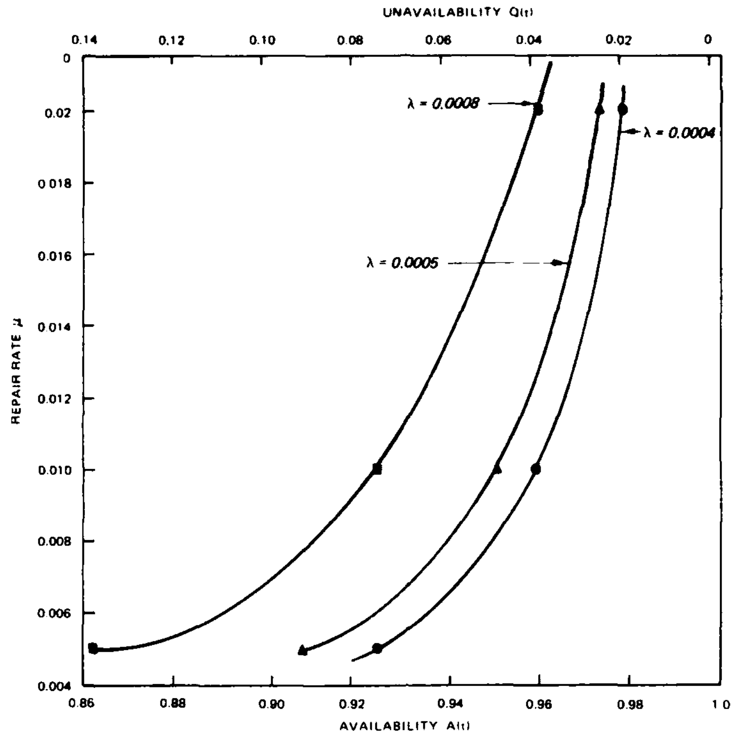

Figure 15. Effect of λ and μ on stationary availability and unavailability

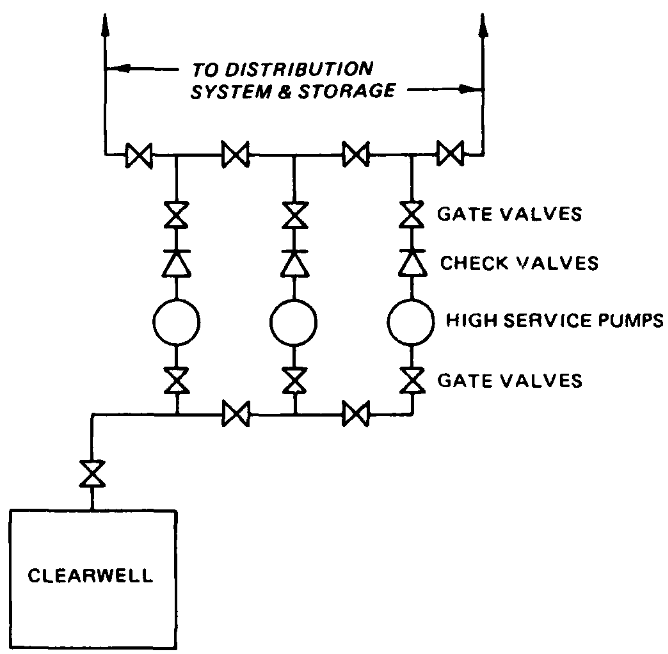

Figure 16. Schematic illustration of a typical water distribution system pumping station

the firm pumping capacity concept and indicates that, for small and medium size water systems, providing firm design capacity with the largest unit out of service gives a reasonable degree of reliability. No guidance is provided on the selection of an appropriate number of pumps. Quantitative guidance concerning the number of pumps to be selected is generally lacking.

Subsystem reliability and availability

151. The first step in analyzing the reliability and availability of the pumping station is to determine the reliability and availability of the individual subsystems within the pumping station. Assuming an exponential failure distribution, a constant failure rate, and a constant repair rate, reliability and availability of the pumping system subsystems can be evaluated analytically. Using the data developed by Shultz and Parr (1981), reliability and availability for the various pumping unit subsystems are presented in Table 13.

Pumping system reliability and availability

152. Once the reliability of the individual subsystems has been computed, the reliability of the individual pumping units can be determined. If it is assumed that each of the subsystems must be in operating condition, the pumping unit can be evaluated as a simple series reliability system. From reliability theory, the reliability of a series system can be computed using Equation 104. Thus, the reliability of the individual pumping units may be calculated as follows.

$$R_s = (RVO_p)(RVO_m)(RVO_c)(RVO_{PT})(RVO_v)^2 \tag{147}$$

where

R_s = reliability of the pumping unit system

RVO_p = reliability of the pump

RVO_m = reliability of the motor

RVO_c = reliability of the control

RVO_{PT} = reliability of the power transmission

RVO_v = reliability of the valves (note one valve on intake and one valve on discharge)

Thus, pumping unit reliability for a 10,000-hr mission life is calculated as follows:

$$R_s = (0.732086)(0.860773)(0.755224)(0.887235)(0.500313)^2$$

$$R_s = 0.105694 \tag{148}$$

For pumping units, reliability is often measured in terms of operational availability, which is a measure of the fraction of calendar time during which the pumping unit was available for service. Using the data collected by Shultz and Parr (1981) and assuming that the unavailabilities of the individual pumping unit subsystems do not intersect, a conservative estimate of pumping unit availability can be calculated in a manner similar to that for reliability using Equation 104. Thus, for a 10,000-hr mission time, the availability of a pumping unit can be calculated as follows:

$$A_S = (0.999703)(0.999897)(0.99936)(0.999956)(0.999197)^2$$

$$A_S = 0.997888 \tag{149}$$

This indicates that the pumping unit will be available for 9,979 hr out of the 10,000-hr mission life, or conversely, during the mission life the pumping unit will be out of service for approximately 21 hr.

Pumping station
<u>reliability and availability</u>

153. The results of the system reliability and availability evaluation are used to analyze component reliability and availability. The component is the pumping station in its entirety. The pump station is essentially a k-out-of-n reliability system. The technique for evaluation of pump station availability can best be illustrated through use of an example computation.

154. A common design practice is to install sufficient pumps to handle peak flows and include a spare pump of equal size to accommodate any downtime of the other pumps. Thus, the capacity of any pump (assuming equal pump sizes) can be calculated using the following formula:

$$Q_p = \frac{Q_T}{(n - 1)} \tag{150}$$

where

Q_p = capacity of the individual pumping units

Q_T = design flow (peak flow)

n = number of pumping units in the pumping stations

155. For any installation, there are $n + 1$ possible capacity states, i.e. $n + 1$ possible pumping capacities. The individual pumping units have two possible operational states: available and unavailable. Letting A represent the percentage of time that a pumping unit is available and Q represent the percentage of time that a pumping unit is not available (note that $Q = 1 - A$), the percentage of time that a pumping station is in each capacity state can be evaluated using Equation 120.

156. For a three-pumping-unit installation, we obtain the following equation:

$$\binom{3}{0} A^3Q^0 + \binom{3}{1} A^2Q^1 + \binom{3}{2} A^1Q^2 + \binom{3}{3} A^0Q^3 \tag{151}$$

Each term in the above equation represents the proportion of time that the system will be at a respective capacity state. For example, the term $\binom{3}{0} A^3Q^0$ yields the percentage of time that three pumps are operational. The state capacity is obtained by multiplying the number of available pumps by the individual unit's pumping capacity. Thus, for a three-pump installation, the following state time proportion matrix can be calculated:

State	Time Proportion	Hours
$3Q_p = \frac{3}{2} Q_T$	0.993653	9936.53
$2Q_p = Q_T$	0.006333	63.33
$Q_p = Q_T/2$	0.000013	0.13
0	0.000001	0.01
	1.000000	10,000.00

The design mission life is 10,000 hr. The estimated number of hours that the pumping station is not expected to be capable of pumping at the combined rate of Q_T is 10,000 - 9999.86 or 0.14 hr. For practical purposes, such a system appears to be 100-percent available to pump the design flows.

Water Distribution Piping

Failure rates

157. Regression equations can be developed for the break rates of water mains using data from specific water distribution systems. As an example, Walski and Pelliccia (1982) developed break rate regression equations for the Binghamton, N.Y., system (Figure 17). These equations are:

$$\text{Pit Cast Iron:} \quad N(t) = 0.02577\, e^{0.0207(t-k)} \tag{152}$$

$$\text{Sandspun Cast Iron:} \quad N(t) = 0.0627\, e^{0.0137(t-k)} \tag{153}$$

where

$N(t)$ = break rate, breaks/mile/year

t = year

k = year of pipe installation

Walski and Pelliccia (1982) state that because of such factors as the severity of different winters, soil conditions, and construction techniques, the break rate may vary significantly between systems and even from year to year within a given system.

158. Walski and Pelliccia (1982) also developed a regression equation for the time required to repair pipe breaks.

$$t = 6.5\, d^{0.285} \tag{154}$$

where

t = time to repair, hr

d = pipe diameter, in.

159. A study of the Philadelphia, Pa., water system (Weiss et al. 1985) developed the time to repair valves tabulated below.

Pipe Diameter in.	MTTR hr
6	8.717
8	9.079
10	11.746
12	16.460
16 & larger	24.360

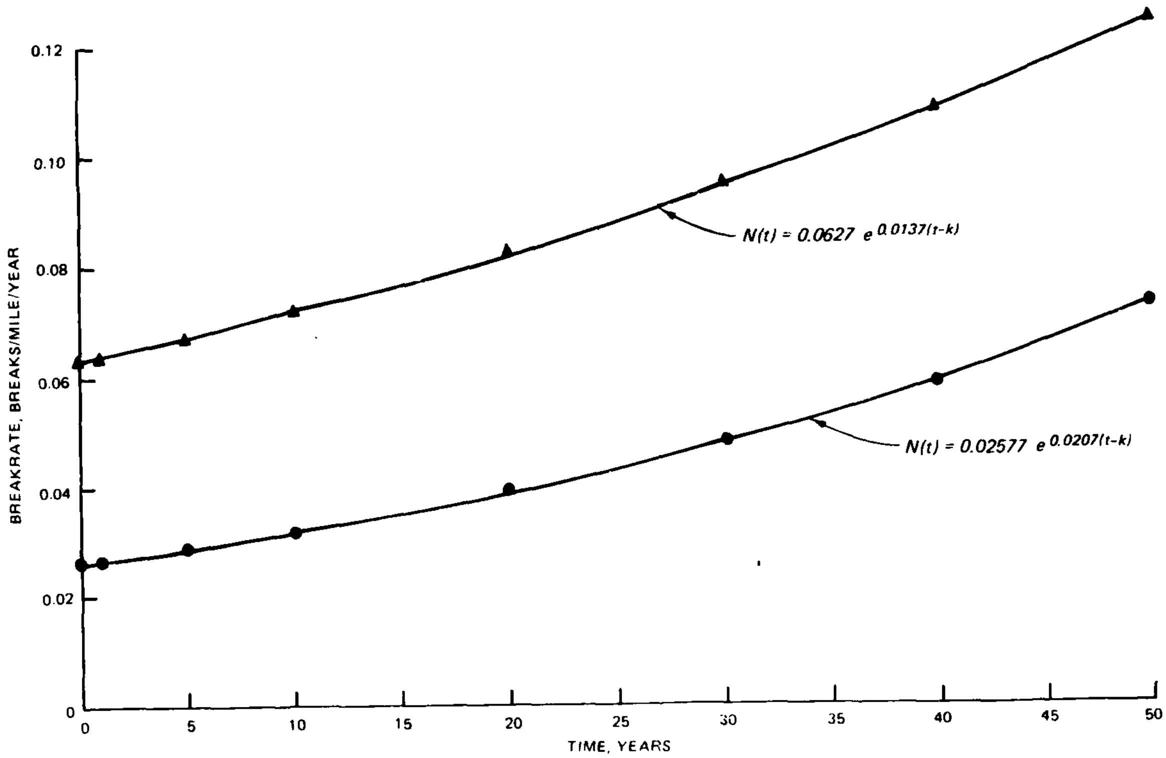

Figure 17. Break rate curves for pit cast iron and sandspun cast iron pipes

Reliability and availability

160. Techniques for evaluating the reliability and availability of water mains can best be illustrated through use of a simple example. Consider a 5-mile water main of sandspun cast iron pipe. From Equation 152, the break rate per year (failure rate) can be calculated as follows:

$$5 \text{ miles} \times N(t) = 5 \times 0.0627\ e^{0.0137(t-k)} = 0.3185\ e^{0.0137(t-k)} \quad (155)$$

161. The reliability for the 5-mile water main can be computed using Equation 65 as follows:

$$R(t) = \exp\left[-\int_0^t (0.3185\ e^{0.0137t})\ dt\right] \tag{156}$$

$$R(t) = \exp\left(-23.25\ e^{\ 0.0137t}\ \Big|_0^t\right) \tag{157}$$

$$R(t) = \exp\left[23.25\ (1 - e^{0.0137t})\right] \tag{158}$$

162. The failure density $f(t)$ can be calculated as:

$$f(t) = \left[0.3185\ e^{0.0137t}\ \exp\ 23.25\ (1 - e^{0.0137t})\right] \tag{159}$$

163. In a similar manner, the reliability based on the failure rate per mile can be calculated to be:

$$R(t) = \exp\left[4.577\ (1 - e^{0.0317t})\right] \tag{160}$$

Reliability curves for various mission times for Equations 158 and 160 are plotted in Figure 18.

164. Determining the availability of a water main is substantially more difficult because the failure rate increases as pipe age increases. Numerical integration or Laplace transform methods may be used to compute availability. However, a simplified procedure can be used to evaluate water main availability if a constant failure rate is assumed. For example, the average failure rate for the above cited 5-mile pipe link can be estimated from Figure 19 to be 0.48. Assuming an MTTR of 16.460 hr (0.69 days or 0.0019 years), the availability can be calculated as follows:

$$A(\infty) = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} = \frac{2.08}{2.08 + 0.0019} = 0.999 \tag{161}$$

An availability of 0.999 indicates that, on average, the main will be out of service approximately 9 hr per year.

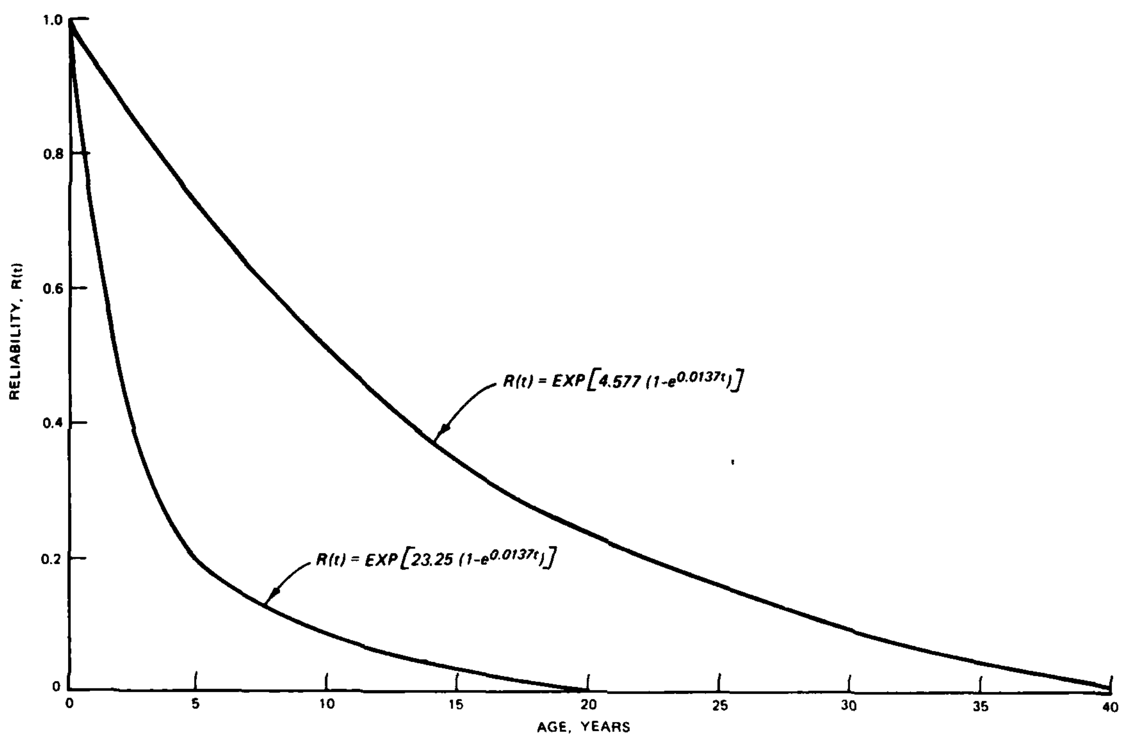

Figure 18. Reliability curves for pipe evaluation example

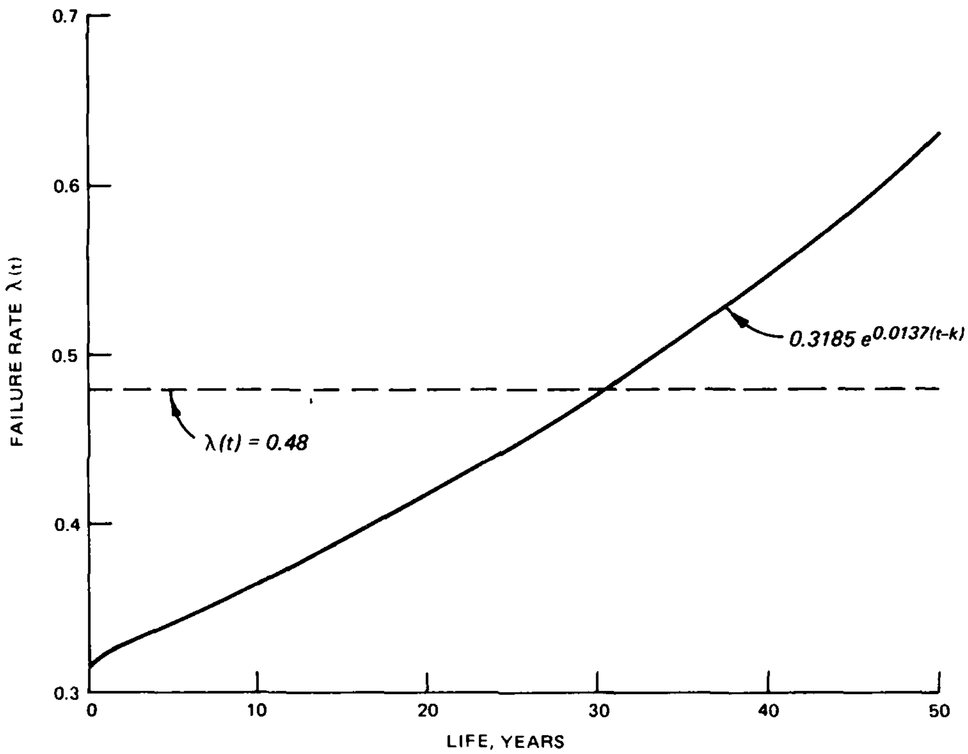

Figure 19. Failure rate curve for sandspun cast iron pipe

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

165. Based on this study, the following conclusions can be drawn:

- a. At present there is no method for optimal (minimum cost) design of looped distribution systems that is completely satisfactory. Existing evaluation methods make no real attempt to explicitly generate and evaluate network layouts in terms of their ultimate importance to the reliability of water service.
- b. Previous optimization models have not considered multiple loadings for various emergency conditions and have not attempted to incorporate any probabilistic or other type of reliability measures into the optimization.
- c. The previous optimization models have made simplifications in cost equations and various constraints in order to solve the problem. Also because of the methodologies used, there are rather severe limitations as to the size of problem (networks) that can be solved.
- d. There is presently no accepted definition or measure of the reliability of water distribution systems.
- e. Only a very few limited studies have dealt with the reliability of water distribution systems. There have not been any procedures or methodologies reported in the literature that could be used to evaluate water distribution system (network) reliability. In fact, there has been little work published in the literature that deals with component (pump, valve, water mains, storage, etc.) reliability.
- f. Most of the published literature dealing with reliability analysis that could be extended to water distribution systems concerns electrical engineering and chemical engineering.
- g. The time to failure type of analysis could be a very important tool for defining water distribution system reliability and availability. Both the repair-to-failure process and the failure-to-repair processes should be used.
- h. The ideas of reliability and unreliability (risk) are fairly common terms to water engineers; however, their probabilistic meanings are not so well known. The concepts of availability and unavailability, which are also probabilistic, are actually more important and should also be considered in the so-called reliability analysis of water distribution networks.
- i. Reliability can be applied to the failure-to-repair process and the repair-to-failure process; however, to consider the whole process (the two combined), the availability and unavailability must be considered.

j. Component reliability analysis methods using stress-strength analysis can be used to determine both static and dynamic (time-dependent) reliability. These concepts also have application to the reliability analysis of components of water distribution systems.

k. Simple series-parallel combination systems can be analyzed quite simply to determine system parameters, e.g. reliability and availability. There have been many network reliability evaluation techniques reported in the literature. Most of the techniques have only been tested on small networks. The most promising methods seem to be the cut set and path enumeration methods and these should be the methods considered for network reliability evaluation of water distribution systems.

l. Another concept that has proven to be very useful in evaluating system failure is the fault tree analysis. Fault tree analysis has shown to be very useful in the field of chemical engineering for the reliability analysis of various types of fluid (chemical) flow processes plants. Of particular interest is the ability to handle time delays such as storage tanks and standby redundancy. The fault tree approach should be further investigated for application to water distribution systems.

m. Even though a great deal of literature has been published on network reliability evaluation, there are few commercial computer codes available that have been tested and proven.

n. The computer code for network reliability evaluation that seems most promising is the DOWNTIME for computing upper and lower bounds for system availability from reliability block diagrams. Other available codes from COADE that may be helpful are the MOCUS or PATH CUT codes to generate the minimal cut sets and minimal path sets. Then use the SUPERPOCUS code to compute system reliability, unavailability, and expected number of failures. All of these codes are available for microcomputers that use the IBM PC operating system.

o. Other codes that may be of interest are the KITT-2 and the KITT-1T codes. The KITT codes are based upon the kinetic tree theory for determining system parameters. The KITT-1T codes include the ability to incorporate time delays provided by storage tanks and to incorporate component (standby) redundancy. The KITT-2 code can handle increasing failure rates.

Recommendations

166. Based on the conclusions presented above, the following recommendations are made:

a. Detailed data for water distribution system operation should be obtained. These data should then be used to preform detailed studies to accomplish the following:

(1) Derive parameters, probability distributions, and failure rate information for distribution components (pipes, pumps, values, storage, and other control devices).

(2) Based upon the results of (1), the concepts and use of the following system parameters should be investigated: reliability, unreliability, availability, unavailability, system failure intensities, mean time to first failure, expected number of failures, etc.

(3) Perform a sensitivity analysis of the various parameters using the collected data and possibly using generated data through a Monte Carlo analysis.

b. Computer codes such as DOWNTIME and KITT-lT that may prove useful for water distribution system analysis should be evaluated using the data obtained in a.

c. Meaningful water distribution system reliability and availability measures should be developed. Specialized computer software for the reliability and availability analysis of the various system components should be developed.

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Table 1

Summary of Selected Water Distribution Network Solvers

Hardy Cross Method
Cross (1936)
Dillingham (1967)
McCormick and Bellamy (1968)
Gilman, Goodman, and Metkowsi (1971)
DeMoyer, Gilman, and Goodman (1973)
Newton Raphson Method
Pitchai (1966)
Liu (1968)
Shamir and Howard (1968)
Epp and Fowler (1970)
Zarghamee (1971)
Lemieus (1972)
Stoner (1972)
Donachie (1974)
Combination of Newton and Hardy Cross
Liu (1968)
Graph Theory Method
Kesavan and Chandrashekar (1972)
Lam and Wolla (1972 a, b)

Table 2

Selected Models for the Optimal Design of Looped Water Distribution Networks

Author	Solution Technique	Decision Variable	Objective Function	Major Assumptions	Algorithm
Jacoby (1968)	Nonlinear programming	Pipe diameters	Minimize cost of pumps and pipes	Diameters treated as continuous variables. No guarantee of global optimality	Numerical gradient technique
Lai and Schaake (1969)	Linear programming	Pipe diameter	Minimize pipe cost	Parameters treated as continuous variables	Model requires specification of head at every node in the network before solving the linear program
Watanatada (1973)	Nonlinear programming	Pipe diameters	Minimize pipe cost	Considered multiple sources. No guarantee of global optimality	Variable metric method of Davison modified by Fletcher and Powell. Problem converted to unconstrained problem by incorporating constraints into objective using penalty terms
Alperovits and Shamir (1977)	Linear programming with gradient computation	Pipe diameters, pumping head, and reservoir elevation	Minimize total cost	Commercial size diameters	Procedure has two levels: the first level solves the linear program model for assumed flow distribution, and then dual variables of the energy line constraints are used to define gradients to change the flow distribution in the network
Cenedese and Mele (1978)	Direct search technique (heuristic)	Pipe diameter	Minimize pipe cost	No guarantee of global optimality	Starts with an open network and then adds loops
Quindry, Brill, and Liebman (1981)	Linear programming with gradient computation	$x = d^{2.63}$ d = diameter	Min $\Sigma\ \beta\ L\ x$ β = cost/length/$d^{2.63}$ L = length of pipe $x = d^{2.63}$	Diameters treated as continuous various, no guarantee of global optimality	Procedure has two levels: the first level solves linear programming for an assumed head distribution in the network and then dual variables are used to define gradients to change the head distribution in the network
Rowell and Barnes (1982)	Separable programming 0-1 integer programming	Pipe diameter and pipe layout	Minimize pipe cost	No guarantee of global optimality. Explicitly considers layout	First level model selects an economical tree layout for the major pipe links and the second level model chooses the loop forming links to add to the first level tree layout

Table 3

<u>Summary of Typical Probability Density Functions*</u>

Distributions → / Parameter ↓	Exponential	Normal	Log-Normal	Weibull	Poisson
pdf, $f(t)$	$\lambda \exp(-\lambda t)$	$\frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right]$	$\frac{1}{\sigma t\sqrt{2\pi}} \exp\left[-\frac{1}{2}(\log t-\mu)^2/\sigma^2\right]$	$\frac{\beta(t-\gamma)^{\beta-1}}{\sigma^\beta} \exp\left[-\left(\frac{t-\gamma}{\sigma}\right)^\beta\right]$	$\frac{e^{-\lambda t}(\lambda t)^n}{n!}$
Unreliability, $F(t)$	$1-e^{-\lambda t}$	$\frac{1}{\sigma\sqrt{2\pi}} \int_0^t \exp\left[-(t-\mu)^2/2\sigma^2\right] dt$	$\frac{1}{\sigma\sqrt{2\pi}} \int_0^t \frac{1}{t} \exp\left[-\frac{1}{2}(\log t-\mu)^2/\sigma^2\right] dt$	$1-\exp\left[-\left(\frac{t-\gamma}{\sigma}\right)^\beta\right]$	$\sum_{i=0}^{n} \frac{(\lambda t)^i}{i!} \exp^{(-\lambda t)}$ (n = no. of failures)
Failure rate, $r(t)$	λ	$\frac{f(t)}{1-F(t)}$	$\frac{f(t)}{1-F(t)}$	$\frac{\beta(t-\gamma)^{\beta-1}}{\sigma^\beta}$	
Mean time to failure	$1/\lambda$	μ	$\exp[(\mu+\frac{1}{2}\sigma^2)]$	$\gamma+\sigma\Gamma\left(\frac{1+\beta}{\beta}\right)$	λt

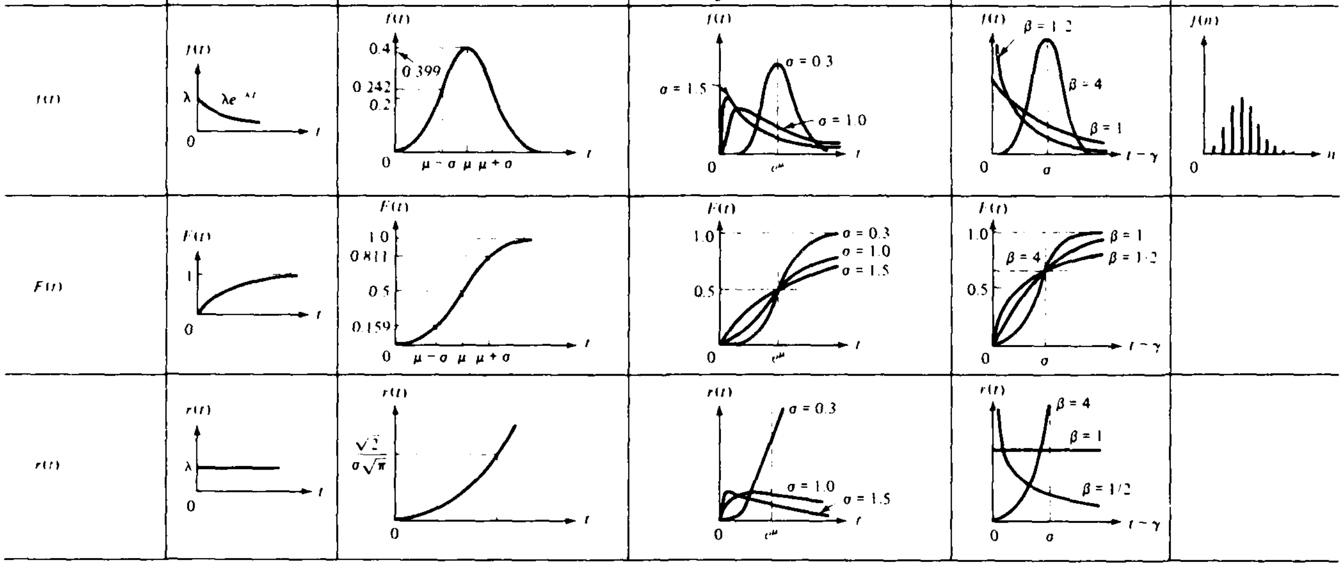

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Table 4

Relations Among Probabilistic Parameters*

		Repairable	Non-repairable
Fundamental Relations	(1)	$A(t)+Q(t)=1$	$A(t)+Q(t)=1$
	(2)	$A(t)>R(t)$	$A(t)=R(t)$
	(3)	$Q(t)<F(t)$	$Q(t)=F(t)$
	(4)	$w(t)=f(t)+\int_0^t f(t-u)v(u)\,du$	$w(t)=f(t)$
	(5)	$v(t)=\int_0^t g(t-u)w(u)\,du$	$v(t)=0$
	(6)	$W(t,t+dt)=w(t)\,dt$	$W(t,t+dt)=w(t)\,dt$
	(7)	$V(t,t+dt)=v(t)\,dt$	$V(t,t+dt)=0$
	(8)	$W(t_1,t_2)=\int_{t_1}^{t_2} w(u)\,du$	$W(t_1,t_2)=\int_{t_1}^{t_2} w(u)\,du = F(t_2)-F(t_1)$
	(9)	$V(t_1,t_2)=\int_{t_1}^{t_2} v(u)\,du$	$V(t_1,t_2)=0$
	(10)	$Q(t)=W(0,t)-V(0,t)$	$Q(t)=W(0,t)=F(t)$
	(11)	$\lambda(t)=\dfrac{w(t)}{1-Q(t)}$	$\lambda(t)=\dfrac{w(t)}{1-Q(t)}$
	(12)	$\mu(t)=\dfrac{v(t)}{Q(t)}$	$\mu(t)=0$
Stationary Values	(13)	MTBF = MTBR = MTTF + MTTR	MTBF = MTBR = ∞
	(14)	$0<A(\infty)<1, 0<Q(\infty)<1$	$A(\infty)=0, Q(\infty)=1$
	(15)	$0<w(\infty)<\infty, 0<v(\infty)<\infty$	$w(\infty)=0, v(\infty)=0$
	(16)	$w(\infty)=v(\infty)$	$w(\infty)=v(\infty)=0$
	(17)	$W(0,\infty)=\infty, V(0,\infty)=\infty$	$W(0,\infty)=1, V(0,\infty)=0$
Remark	(18)	$w(t)\neq\lambda(t), v(t)\neq\mu(t)$	$w(t)\neq\lambda(t), v(t)=\mu(t)=0$
	(19)	$\lambda(t)\neq r(t), \mu(t)\neq m(t)$	$\lambda(t)=r(t), \mu(t)=m(t)=0$
	(20)	$w(t)\neq f(t), v(t)\neq g(t)$	$w(t)=f(t), v(t)=g(t)=0$

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Table 5

Reliability and Maintainability by Subsystem Type

(Shultz and Parr 1981)

Subsystem	MTBF ($\times 10^6$ hr)	MTTR (hr)
Pumps	0.032066	9.541
Power transmission	0.035620	2.273
Motors	0.066700	6.854
Valves	0.014440	11.615
Controls	0.083580	3.696

Table 6

Subsystem Reliability and Maintainability by Generic Group

(Shultz and Parr 1981)

Subsystem	MTBF ($\times 10^6$ hr)	MTTR (hr)
Pumps		
Centrifugal, open impeller	0.021660	7.825
Axial flow, propeller	0.074191	16.780
Power transmission		
Concentric reducer	0.122640	2.000
Parallel shaft	0.710910	32.000
Right angle shaft	0.019480	1.400
Vertical shaft	0.031470	2.023
Variable speed, hydraulic	0.349500	--
Variable speed, other	0.014200	2.500
Gear box	0.045780	3.530
Chain drive	0.017850	8.000
Belt drive	0.091010	1.800
Motors		
Multiphase	0.068000	6.853
Variable speed, AC	0.114820	8.000
Gas engine	0.023800	24.000
Valves		
Gate	0.008930	3.636
Ball	0.0[illegible]460	--
Butterfly	0.0[illegible]590	1.000
Plug	0.028520	--
Controls		
Electrical	0.100640	2.893
Mechanical	0.031230	8.000
Pressure (fluid)	0.035780	8.236
Pressure (air)	0.018690	3.556

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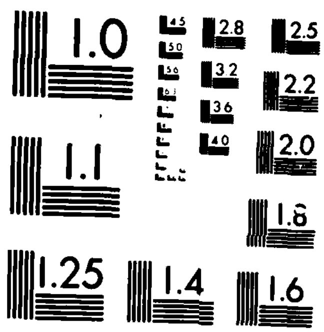

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Table 7

Subsystem Reliability and Maintainability by Size

(Shultz and Parr 1981)

Subsystem	MTBF ($\times 10^6$ hr)	MTTR (hr)
Pumps, gpm		
1-10,000	0.039600	6.786
10,001-20,000	0.031100	7.800
20,001-100,000	0.081635	26.722
Over 100,000	0.008366	9.368
Power transmission, hp		
0-1	0.025370	1.815
2-5	0.011010	2.116
6-25	1.376400	25.000
26-100	0.058620	5.000
101-500	0.078380	2.600
Over 500	0.206450	32.000
Motors, hp		
0-1	0.206450	2.600
2-5	0.214700	--
6-25	0.565600	7.857
26-100	0.062100	4.967
101-500	0.046000	12.685
Over 500	0.064630	7.658
Valves, in.		
6-12	0.054590	--
13-24	0.010810	1.000
25-48	0.019070	42.000
Over 48	0.007500	2.667
Controls, hp		
0-1	2.009200	2.050
2-5	0.509500	--
6-25	4.684900	--
26-100	0.026109	2.377
101-500	0.099340	5.450
Over 500	0.037700	3.125

Table 8

Comparison of MTBF for Subsystems for Three Data Sources

Subsystem	Shultz and Parr (1981)			Southwest Research Institute (1978)*			Reliability Analysis Center (1981)**		
	Operating Hours ($\times 10^6$)	Number of Failures	MTBF Hours ($\times 10^6$)	Operating Hours ($\times 10^6$)	Number of Failures	MTBF Hours ($\times 10^6$)	Operating Hours ($\times 10^6$)	Number of Failures	MTBF Hours ($\times 10^6$)
Pumps, centrifugal	2.11746	97	0.021662	14.1340	324	0.44910	5.176	36	0.14123
Pumps, axial	1.75462	23	0.074191	0.4540	1	0.27023	--	--	--
Power transmission	11.10382	311	0.035620	4.1240	58	0.07020	37.480	303	0.12339
Motors, multiphase AC	12.49470	183	0.068000	29.0500	112	0.25760	7.288	9	0.75520
Motors, internal combustion	0.03976	1	0.023800	3.5230	102	0.03429	--	--	--
Valves									
Ball	0.01916	1	0.011460	0.1340	1	0.0798	11.192	10	1.08400
Butterfly	0.05475	1	0.032590	32.1290	62	0.5040	13.675	18	0.73320
Gate	0.10402	11	0.008930	5.2140	26	0.1956	7.484	10	0.70270
Plug	0.01916	0	0.025820	1.2880	8	0.1489	5.806	19	0.29550

* Nuclear plant reliability data system.
** Nonelectric parts reliability data.

Table 9

Gate Symbols (Henley and Kumamoto 1981)*

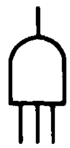
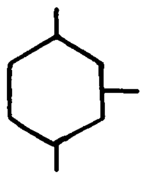
	GATE SYMBOL	GATE NAME	CAUSAL RELATION
1		AND GATE	OUTPUT EVENT OCCURS IF ALL INPUT EVENTS OCCUR SIMULTANEOUSLY.
2		OR GATE	OUTPUT EVENT OCCURS IF ANY ONE OF THE INPUT EVENTS OCCURS.
3		INHIBIT GATE	INPUT PRODUCES OUTPUT WHEN CONDITIONAL EVENT OCCURS.
4		PRIORITY AND GATE	OUTPUT EVENT OCCURS IF ALL INPUT EVENTS OCCUR IN THE ORDER FROM LEFT TO RIGHT.
5		EXCLUSIVE OR GATE	OUTPUT EVENT OCCURS IF ONE, BUT NOT BOTH, OF THE INPUT EVENTS OCCUR.
6		m OUT OF n GATE (VOTING OR SAMPLE GATE)	OUTPUT EVENT OCCURS IF m OUT OF n INPUT EVENTS OCCUR.

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Table 10

Event Symbols (Henley and Kumamoto 1981)*

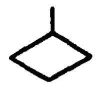
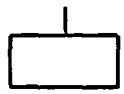
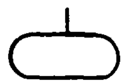
	EVENT SYMBOL	MEANING OF SYMBOLS
1	 CIRCLE	BASIC EVENT WITH SUFFICIENT DATA
2	 DIAMOND	UNDEVELOPED EVENT
3	 RECTANGLE	EVENT REPRESENTED BY A GATE
4	 OVAL	CONDITIONAL EVENT USED WITH INHIBIT GATE
5	 HOUSE	HOUSE EVENT. EITHER OCCURRING OR NOT OCCURRING
6	 TRAINGLES	TRANSFER SYMBOL

Table 11

Heuristic Guidelines for Fault Tree Analysis*

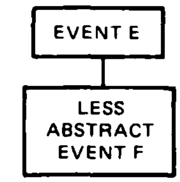
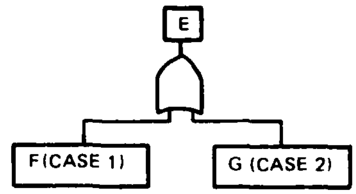
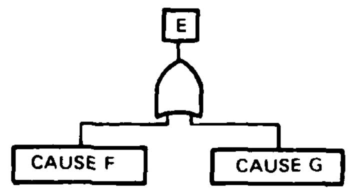
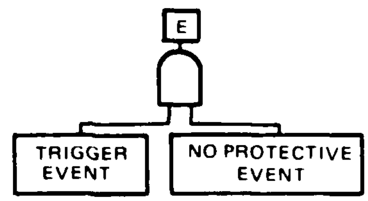
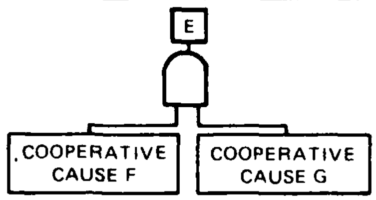
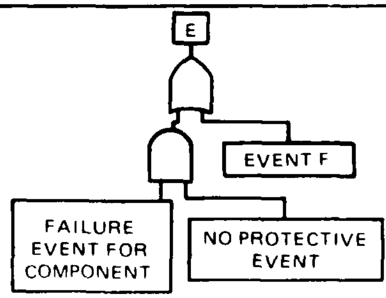
	DEVELOPMENT POLICY	CORRESPONDING PART OF FAULT TREE
1	EQUIVALENT BUT LESS ABSTRACT EVENT F	
2	CLASSIFICATION OF EVENT E	
3	DISTINCT CAUSES FOR EVENT E	
4	TRIGGER VERSUS NO PROTECTIVE EVENT	
5	COOPERATIVE CAUSE	
6	PINPOINT A COMPONENT FAILURE EVENT	

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Table 12

Reliability, Unreliability, Availability, and Unavailability

Data for λ = 0.0008/hr and μ = 0.02/hr

Time (hr)	Reliability	Unreliability	Availability	Unavailability
0	1.	0.	1.	0.
10	0.9917	0.0083	0.9925	0.0075
20	0.9834	0.0166	0.9637	0.0363
30	0.9753	0.0247	0.9814	0.0186
40	0.9672	0.0328	0.9774	0.0226
50	0.9592	0.0408	0.9741	0.0259
100	0.9200	0.0800	0.9650	0.0350
200	0.8465	0.1535	0.9606	0.0394
300	0.7788	0.2212	0.9601	0.0399
400	0.7165	0.2835	0.9600*	0.0400*
500	0.6592	0.3408	0.9600	0.0400
1000	0.4346	0.5654	0.9600	0.0400
2000	0.1889	0.8111	0.9600	0.0400
3000	0.0821	0.9179	0.9600	0.0400
4000	0.0357	0.9643	0.9600	0.0400
5000	0.0155	0.9845	0.9600	0.0400
10000	0.0002	0.9998	0.9600	0.0400

* Point of stationary availability and unavailability.

Table 13

Summary of Pumping Unit Subsystem Reliability and Availability

Mission Life (hr)	Pumps		Motors		Power Transmission		Controls		Valves	
	Reliability	Availability	Reliability	Availability	Reliability	Availability	Reliability	Availability	Reliability	Availability
0	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
1	0.999969	0.99997	0.999985	0.999986	0.999972	0.999977	0.999988	0.99999	0.999931	0.99934
2	0.999938	0.999944	0.999955	0.999974	0.999944	0.999963	0.999976	0.999982	0.999862	0.999873
3	0.999907	0.99992	0.999955	0.999964	0.999916	0.999953	0.999964	0.999976	0.999792	0.999817
4	0.999875	0.999898	0.99994	0.999955	0.999888	0.999947	0.999952	0.999971	0.999723	0.999766
5	0.999844	0.999879	0.999925	0.999947	0.99986	0.999943	0.999994	0.999967	0.999654	0.999719
6	0.999813	0.999861	0.99991	0.99994	0.999832	0.999941	0.999928	0.999965	0.999585	0.999676
7	0.999782	0.999845	0.999895	0.999934	0.999804	0.999939	0.999916	0.999963	0.999516	0.999636
8	0.000751	0.999831	0.99988	0.999929	0.999776	0.999938	0.999904	0.999961	0.999446	0.9996
9	0.99972	0.999818	0.999865	0.999925	0.999747	0.999937	0.999892	0.99996	0.999377	0.999566
10	0.999688	0.999807	0.99985	0.999921	0.999719	0.999937	0.999881	0.999959	0.999308	0.999536
20	0.999377	0.999739	0.9997	0.999903	0.999439	0.999936	0.999761	0.999956	0.998616	0.99934
30	0.999065	0.999715	0.99955	0.999899	0.999158	0.999936	0.999641	0.999956	0.997925	9.999257
40	0.998753	0.999707	0.999401	0.999898	0.998878	0.999936	0.999522	0.999956	0.997234	0.999222
50	0.998442	0.999704	0.999251	0.999897	0.998597	0.999936	0.999402	0.999956	0.996543	0.999207
60	0.998131	0.999703	0.999101	0.999897	0.998317	0.999936	0.999283	0.999956	0.995854	0.999201
70	0.997819	0.999703	0.998951	0.999897	0.998037	0.999936	0.999163	0.999956	0.005164	0.999198
80	0.997508	0.999703	0.998801	0.999897	0.997757	0.999936	0.999043	0.999956	0.994475	0.999197
90	0.997197	0.999703	0.998652	0.999897	0.997477	0.999936	0.998924	0.999956	0.993787	0.999197
100	0.996886	0.999703	0.998502	0.999897	0.997197	0.999936	0.998804	0.999956	0.993099	0.999197
1,000	0.969296	0.999703	0.985119	0.999897	0.972316	0.999936	0.988107	0.999956	0.933092	0.999197
10,000	0.732086	0.999703	0.860773	0.999897	0.755224	0.999936	0.887235	0.999956	0.500313	0.999197
100,000	0.044221	0.999703	0.223298	0.999897	0.060361	0.999936	0.302263	0.999956	0.000982	0.999197

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APPENDIX B: AVAILABLE COMPUTER CODES FOR RELIABILITY ANALYSIS

Background

1. Although a great deal of literature has been published on network reliability evaluation, there are few proven computer codes available. This appendix presents a brief discussion of several computer codes that have been developed for risk and reliability evaluation.

2. Henley and Kumamoto (1981) identified several computer codes with application to risk and reliability analysis:

<u>a</u>. Program title: KITT-IT

Abstract: Top-event parameters Q_s, W_s, λ_s for systems using kinetic tree theory (augmented KITT program which handles storage tanks and standby redundancy).

Number of source statements: 1,361

User manual: 24 pages

<u>b</u>. Program title: PATH-CUT

Abstract: Conversion of minimal path sets into minimal cut sets, and vice versa, using a classification method.

Number of source statements: 250

User manual: 15 pages

<u>c</u>. Program title: PROTECT

Abstract: Based on a fault tree for a plant and two fault trees for a protective system, the computer code produces time profiles of expected numbers of normal trips, spurious trips, and destructive hazards.

Number of source statements: 340

User manual: 75 pages

<u>d</u>. Program title: PITE

Abstract: Simplifying decision tables using Quine's consensus theory.

Number of source statements: 940

User manual: 200 pages

<u>e</u>. Program title: PRIME

Abstract: Generating prime implicants for noncoherent fault trees by using a classification method.

Number of source statements: 980

User manual: 40 pages

f. Program title: MARKOV

Abstract: This code calculates time profiles of state probabilities for a Markov transition diagram. State transition matrix is used for numerical integration of linear differential equations.

Number of source statements: 310

User manual: 15 pages

g. Program title: NLB (New Lawler and Bell)

Abstract: Redundancy optimization using Lawler and Bell's integer programming.

Number of source statements: 320

User manual: 15 pages

h. Program title: HEUR

Abstract: Reliability optimization under constraints on cost, weight, etc., by using a heuristic approach.

Number of source statements: 310

User manual: 20 pages

i. Program title: SCHE

Abstract: Conversion of reliability block diagrams into fault trees.

Number of source statements: 970

User manual: 40 pages

j. Program title: CONVERSION

Abstract: Obtains minimal cut sets through expansion of product of sum expression of top event, given minimal path sets.

Number of source statements: 220

User manual: 20 pages

k. Program title: FAMULS (Fault Tree for Multi-Loop Systems)

Abstract: Generating cut sets for systems with multiple control loops, given signal flow graph representation of plant.

Number of source statements: 620

User manual: 40 pages

3. The following eight computer programs are available from JBF Associates, 10700 Dutchtoun Drive, Knoxville, Tennessee 37922. Those with an asterisk are also available from the Argonne National Laboratory, Code Center, Argonne, Illinois 60439.

a. *Program title: MOCUS

Abstract: Obtains minimal cut sets or path sets for fault trees with AND/OR and INHIBIT logic.

Minimum core: 228K (IBM)

Number of source statements: 1,800

b. *Program title: PREP

Abstract: Obtains cut sets or path sets from fault trees with AND/OR and INHIBIT logic using combinatorial testing.

Number of source statements: 1,200

c. Program title: BACFIRE

Abstract: Aids in common cause failure analysis by commonality searches.

Number of source statements: 800

d. *Program title: KITT-1

Abstract: For calculating top-event parameters Q_s, W_s, λ_s given cut sets and failure and repair rates for components. Uses kinetic tree theory.

Number of source statements: 1,800

e. *Program title: KITT-2

Abstract: A version of KITT-1 which permits the input of time-varying failure and repair rates.

Number of source statements: 1,700

f. *Program title: SAMPLE

Abstract: Uses Monte Carlo techniques to obtain confidence limits for top events, given confidence limits for component failure and repair rates.

Number of source statements: 400

g. Program title: SUPERPOCUS

Abstract: A simplified KITT which uses bounding theorems to approximate top-event probabilities. Also calculates Fussell-Vesely important.

Number of source statements: 600

h. Program title: TREDA

Abstract: Draws report-quality fault trees using a CALCOMP plotter.

Number of source statements: 3,700

4. The firm Computer Aids for Design Engineers and Scientists (COADE), 8550 Katy Freeway, Suite 122, Houston, Texas 77024, telephone (713) 973-9060,

sells a number of computer codes applicable to risk and reliability analysis. The computer codes sold by COADE are designed to run under the IBM PC operating system. These programs can be installed on microcomputers or mainframe computers. A list of the available programs and a brief description are given below:

a. DOWNTIME (formerly RELICS) Systems Reliability. DOWNTIME evaluates the upper and lower bounds for system availability, mean time to failure, mean time to repair, as well as component importance. It uses reliability block diagrams with one source and one sink node. Cut sets and path sets are computed and displayed. DOWNTIME requires data on component mean time to failure, mean time to repair, and the block diagram structure. DOWNTIME can handle up to 50 blocks.

b. MARKOV Systems Analysis by the Markov Method. MARKOV numerically integrates a set of differential equations to give a Markov transition diagram. System characteristics such as availability and reliability can be output in response to user specifications. The program automatically generates the differential equations from node-arc relationships of the transition diagram. Applications of MARKOV include:

(1) Common cost analysis.

(2) Standby redundancy.

(3) Mission reliability.

(4) Availability analysis.

(5) Sequential failure.

(6) Statistically dependent failures.

Arcs and nodes can be readily deleted or added. This makes the program ideal for sensitivity analysis. Transition rates can also be easily changed. Up to 50 nodes can be handled and 100 characteristics of the diagram can be output.

c. BACFIRE Common Cause Analysis. A common cause failure analysis is an essential part of complete system safety and reliability analysis. BACFIRE searches for common potential causes of failure among the basic events of a minimal cut set of the system logic model. A minimal cut set with a common potential cause of failure is called a common cause candidate. When a common cause candidate is identified, it is listed with its common potential cause of failure as output from BACFIRE.

d. SUPERPOCUS Systems Analysis from Cutsets. SUPERPOCUS is used during quantitative reliability, safety, and risk evaluations. Given minimal cut sets and mean times to failures of system components, SUPERPOCUS will calculate system probabilistic reliability and safety characteristics, employing tightly bounded approximation methods. Results include time-dependent reliability characteristics such as unavailability, reliability, and expected number of failures in the system. Data can be

passed to SUPERPOCUS from the qualitative reliability programs MOCUS, PATH-CUT, and DOWNTIME.

e. MOCUS Cutsets and Path Sets for Fault Trees. From a given graphical representation of a fault tree (Boolean logic failure), the system failure modes (called the minimal cut sets) and the system success modes (called the minimal path sets) can be determined by MOCUS. Input can be control parameters specifying

(1) the minimal cut set length to be obtained.

(2) the type of minimal sets to be obtained.

(3) the output options.

A description of the fault tree is also needed. MOCUS is a thoroughly tested, widely used program.

f. SCHE Block Diagrams to Fault Trees. Given a process block (reliability) diagram, SCHE will generate a fault tree, the top event being the failure of all system paths. The fault tree produced is a true, sequential representation of possible modes of system failure. The program is useful for sensitivity analyses insofar as the blocks can be changed, deleted, or added. Output nodes can be moved and manipulated. SCHE generates fault trees for block diagrams having up to 50 nodes.

g. SAMPLE Confidence Limits of Top Events. SAMPLE uses the Monte Carlo sampling technique to obtain the mean, standard deviation, probability range, and distribution for a multivariable function. The independent variables are, for example, component reliabilities being subject to statistical variations and the dependent variable such as the system reliability. Given values for the location and dispersion parameters of the independent variables, and a specific input distribution, SAMPLE obtains a Monte Carlo sample of the independent variables and evaluates the corresponding function. The program has three output distributions: normal, lognormal, and log-uniform. SAMPLE is very useful because system characteristics such as reliability and availability can be evaluated as a range and not a point estimate.

h. PATH CUT Minimal Path to Minimal Cut Sets. PATH CUT converts minimal path cuts into minimal cut sets using a classification method. This is a top-down approach which converts the smaller number of path sets (which can be found by inspection of reliability block diagrams, or by MOCUS or RELICS) into cut sets without a pairwise comparison of redundant sets. Hence, PATH CUT is faster and more efficient than MOCUS-based algorithms. A path set can be added or deleted easily, facilitating sensitivity analyses. PATH CUT can convert as many as 50 path sets with a maximum of 50 elements into minimal cut sets. Cut sets are output one by one as they are identified, and thus the program can generate a large number of cut sets without any memory requirements.

i. HEURI Redundancy Optimization. Given a reliability block diagram, HEURI will yield the optimal number of redundant

components to be allocated to each block while maximizing the system reliability and meeting with constraints such as cost, weight, and volume. HEUR1 solves the redundancy optimization problem by a heuristic integer programming technique which is based on a steepest ascent in one neighborhood. Each local optimum reached is checked for optimality in two neighborhoods. Constraints can be relaxed, narrowed, deleted, or added, thus facilitating sensitivity analysis. Up to 50 blocks can be handled.

j. HEUR2 Redundancy Allocation. HEUR2 is an advanced version of HEUR1. Given a reliability block diagram, the program will yield the optimal number of redundant components to be allocated to each block, while maximizing the system reliability and meeting with constraints such as cost, weight, and volume. HEUR2 uses a steepest ascent in two neighborhoods rather than an ascent in one neighbor as in HEUR1. Constraints can be relaxed, narrowed, deleted, or added. HEUR2 will generate a solution close to the global optimum, starting from trivial initial guesses. Up to 40 blocks can be handled.

k. CONVERSION Minimal Paths to Minimal Cut Sets. Reliability block diagrams and fault trees usually have a smaller number of path sets than cut sets. The minimal path sets can be found easily by inspection or by use of MOCUS or RELICS. Given a number of path sets, CONVERSION inverts them into minimum cut sets by expansion of a product of a sum expression of the top events with absorption of redundant terms. A path set can be added or deleted, facilitating sensitivity analysis. CONVERSION can handle as many as 50 paths with a maximum of 50 elements. It generates as many as 800 minimal cut sets with a maximum size of 11.

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